Supergen Bioenergy

SUSTAINABLE BIOENERGY SYSTEMS FOR OUR LOW-CARBON FUTURE

Report from the Supergen Bioenergy Hub Stakeholder Workshop on Novel Crops and Forestry Species as Sources of Industrial Biomass

Engineering and Physical Sciences Research Council

Biotechnology and Biological Sciences Research Council

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The Supergen Bioenergy Hub works with academia, industry, government and societal stakeholders to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future.

The Hub is funded jointly by the Engineering and Physical Sciences Research Council (EPSRC) and the Biotechnology and Biological Sciences Research Council (BBSRC) and is part of the wider Supergen Programme.

ISBNs

Print: 978-1-85449-817-5

Electronic: 978-1-85449-818-2

You can download this publication from: www.supergen-bioenergy.net/outputs

All enquiries related to this publication should be sent to: supergen-bioenergy@aston.ac.uk

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Thanks to all workshop attendees for their input on the day and to the Birmingham Institute of Forest Research (BIFoR) staff for hosting the event.

Disclaimer

The information contained within this report originates from workshop participants and unless peer-reviewed literature is cited it does not contain independently verified scientific information attributable to Supergen Bioenergy Hub.

Executive Summary

This report is the output of the Supergen Bioenergy Hub Stakeholder Workshop on Novel Crops and Forestry Species as Sources of Industrial Biomass held on 11 May 2023 at the Birmingham Institute of Forest Research (BIFoR) facility. The workshop brought together producers, end-users, policymakers, and researchers with experience and knowledge of novel biomass crops and forestry species suitable for industrial-scale production of biomass, with the aim of identifying: A list of plausible novel biomass crops for near-term deployment in the UK; the key information needed to enable the sustainable deployment of novel biomass crops in the UK; a summary of the key information and information sources known to participants for a subset of these novel crops; and research priorities .

The workshop focused on species that: could be grown in the UK climate; would be suitable for industrial-scale production of bioenergy or bio-based materials (i.e., not crops for the production of low-volume, high-value speciality products, such as direct production of pharmaceuticals); could be deployed at scale in the near term (< 5yrs); and are not yet being produced at scale in the UK. Drawing on the collective knowledge of the participants, the workshop identified 27 novel species considered suitable for deployment in the UK in the near to medium term. These crops included annual forbs, perennial forbs, energy grass, tree species, shrubs, and conservation biomass.

Participants identified the key pieces of information that would enable the community to select, sustainably deploy, and utilise suitable novel biomass crops within the UK. For a subset of the novel biomass crops identified (energy grasses, black locust, paulownia, eucalyptus, hemp, cup plant, sphagnum moss) the participants used their knowledge to address some of the information needs, identified other sources of this information and highlighted areas where further research is needed.

Key Findings:

- Participants highlighted that any successful deployment of novel biomass crops in the UK needs to be underpinned by first-hand experience and data. Therefore, there is a critical role for the support for UK field trials, encompassing both crop growth and utilisation, and robust data collection, from either the industry or government.
- Basic agronomic knowledge was seen as key in being able to facilitate the deployment of novel biomass crops. Furthermore, an understanding of the environmental impacts, the nature and location of current and future markets, and the political acceptability of different crops will all play a role in determining the likely, and desirable, deployment pattern of novel biomass crops across the UK. Potential invasiveness was also noted by participants as a key knowledge need when assessing the viability and desirability of novel biomass crops.
- Information provided by the participants suggested novel biomass crops differ in their agronomic needs, the nature of the feedstocks produced and the potential environmental impacts, highlighting the need to consider multiple factors in the decision-making process. Many of the crops had specific needs, which could result in localised, but not regional, restrictions of deployment.
- The main limitations in the information known to the participants were associated with the potential impacts of future climates on crop yields, and the environmental impacts of large-scale production on biodiversity and other ecosystem services such as soil health and carbon sequestration.

- Cross-cutting research needs across all crop types were identified, with the recognition of the need for: agronomic trials; independent assessment of impacts on ecosystem services (especially biodiversity and carbon); exploration of the impacts of future climates (in particular, impacts of extreme weather events such as heatwaves and droughts); the development of new agronomic machinery; exploration of new markets and end-users; the development of pathways for upscaling the production of planting material; and crop breeding to ensure continual improvement of crop traits.

- Peer-reviewed research on novel biomass crops is limited, with much of the information identified by participants based on personal experience and grey literature. The workshop identified a limited number of commercial scale trials, but often those that do exist aren't being assessed by truly independent bodies. The workshop highlighted the need for independent research and verification, especially in relation to the environmental impacts of large-scale production on a range of ecosystem services, including soil health and carbon sequestration, as well as biodiversity.

Introduction

As we transition to net zero and reduce our reliance on fossil feedstocks, biomass will play an important role as a feedstock for the production of both energy and materials. To support this, more biomass from purpose-grown biomass crops and forestry will be required[1,2]. At the moment, increased deployment of current biomass crops such as willow SRC and miscanthus is envisioned, but with increasing demand, changing climates and new end markets, more novel biomass crops and forestry species may also become important in the future.

It is essential that any expansion of biomass cropping is sustainable, economically viable, and appropriately scaled to meet future feedstock demands. As recognised in the UK Government's recently published Biomass Strategy[2], sustainability criteria will need to be adjusted and developed to account for the unique and diverse nature of novel biomass crops. This will require an understanding of the biomass crops that may be deployed, for example around agronomic practices, yields, or environmental impacts.

The difficulty is that for novel biomass crops there is still a degree of uncertainty, with knowledge gaps that have yet to be addressed. Traditional sources of information such as scientific literature are often limited for these crops, so it is critical to consider informal data and knowledge held by individuals involved in the development and utilisation of these crops, and to identify where more rigorous scientific study is required. In an effort to do just this, the Supergen Bioenergy Hub organised a workshop on novel crops and forestry species as sources of industrial biomass, and this report reflects the discussions and information gathered at this event. The workshop brought together key stakeholders from academia, policy, and industry, with the aim of gathering insights on the most promising novel biomass crops for the UK, understanding the critical information needs for sustainable, large-scale crop deployment, and identifying key experts and information sources to support future work on this topic.

Workshop scope

The workshop targeted novel crops and forestry species that: can be grown in the UK climate; are suitable for industrial-scale production of bioenergy or bio-based materials (i.e., not crops for production of low-volume, high-value speciality products, such as direct production of pharmaceuticals); could be deployed at scale in the near term (< 5yrs); and are not currently being produced at scale in the UK. For simplicity, these novel crops and forestry species are hereon referred to collectively as novel biomass crops.

Micro and macro algae systems were not within the scope of this workshop because discussion of these systems would require a different set of expertise than that required for discussions on terrestrial agricultural crops, conservation biomass and forestry. Biomass crops and forestry species with established UK markets such as short rotation coppice willow and poplar, miscanthus, and maize were also ruled out.

Participants

Attendance at the workshop was focused on those with first-hand experience of working with novel biomass crops, either in a research or commercial setting, and those working in

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[1] Sixth Carbon Budget. Climate Change Committee (2020)

[2] Biomass Strategy 2023. Department for Energy Security and Net Zero.

related policy areas. The workshop had a total of **32 participants** from different stakeholder groups:

- 2 agronomists (i.e., researchers/industry representatives with grower experience)
- 1 end user (i.e., organisations using the novel crop as a product/feedstock)
- 7 growers (i.e., organisations/individuals growing novel biomass crops)
- 5 policymakers (i.e., attendees from government departments)
- 17 researchers (working on: conversion technologies, crop genetics, sustainability and, policy)

Workshop format

The workshop was held at the Birmingham Institute of Forest Research (BIFoR) facility near Stafford, UK on 11 May 2023. The formal workshop started after a morning tour of the free air carbon enrichment (FACE) experimental platform at BIFoR.

The workshop began with a series of scene setting presentations from Dr Rebecca Rowe (UK Centre for Ecology and Hydrology), who introduced the workshop, Hartley Stoddard (Department for Environment, Food and Rural Affairs (Defra)), who gave a policy perspective on novel biomass crops, and Professor Jason Hallett (Imperial College), who presented on the utilisation of novel biomass crops for materials and energy production.

Short introductory talks were given by attending participants with expertise on selected novel biomass crops (slides available to download below):

- Alan Gay, IBERS, Aberystwyth University – Hemp presentation
- Dr Elaine Jensen, IBERS, Aberystwyth University – Reed Canary Grass presentation
- Mike Cooper, Miscanthus Nursery & New Energy Farms – Novel Grasses presentation
- Marton Nemeth, Silvanus Forestry – Black Locust presentation
- Tim Wood, Newtone – Cup Plant presentation

After the presentations, there were a series of discussion sessions that were designed to gather input from participants on a range of aspects related to novel biomass utilisation:

- Part 1: What are the most promising novel biomass crops for deployment in the UK?
- Part 2: What do we need to know about novel biomass crops?
- Part 3: What information do we already have on novel biomass crops?
- Part 4: Where is further research needed?

In these sessions, participants worked in groups facilitated by Supergen Bioenergy Hub researchers. For parts 1 and 2, they were asked to assign themselves to one of four groups according to their area of expertise: crop production; policy; end use/conversion technologies; and sustainability/systems analysis. For part 3 the groups focused on different subsets of novel biomass crops, and participants were asked to assign themselves to the group looking at the type of crops they had the most expertise in.

Input was captured by participants and facilitators writing comments on sticky notes, and during feedback at the end of each session when each group contextualised their notes with wider discussion and clarifications.

After the workshop comments on sticky notes were recorded and tabulated to allow review, grouping, and analysis. Further information was gathered by following up on information sources identified on the sticky notes (e.g., named reports, or journal papers), presented within the slides, and by contacting key experts named by the break-out groups.

Part 1 - What are the most promising novel biomass crops for deployment in the UK?

In their groups, participants addressed the question of what they considered the most promising novel biomass crops for deployment in the UK. A total of 27 novel biomass crops were listed (Table 1), and this included annual forbs (6), perennial forbs (3), tall grasses (3), small grasses (4), tree species (5), shrubs (2), conservation biomass (4), and sphagnum moss. Table 1 lists the novel biomass crops identified during the workshop and in the post-workshop review. These have been classified as examples of novel use or novel species.

Novel use refers to crops that are already grown in the UK for other purposes, meaning that utilisation as biomass represents a secondary or additional use of these species. Fifteen, just over half, of the crops identified were classified as novel use. For most of these crops, planting material (seeds or cutting) and agronomic information is available from multiple sources including commercial companies. However, producing these crops for use as biomass feedstocks may result in changes in agronomic practices, new varieties being developed, or expansion of the crop into new areas, all of which raise the need for additional information and data collection.

The remaining 12 species suggested by workshop representatives were classified as novel species. Novel species are those that are not currently grown at scale in the UK, meaning they are novel biomass crops for which biomass would be the primary market. In these cases, knowledge of agronomic practices, at least within the UK, is limited to small specialist companies and individuals.

Table 1: Novel biomass crops and tree species with potential for UK production, as identified by workshop participants.

Group	Common name	Scientific name	Novel species / Novel use
Annual forbs	Borage	*Borage officinalis*	Use
	Phacealia	*Phacelia tanacetifolia*	Use
	Fodder kale	*Brassica*	Use
	Hemp	*Cannabis sativa cultivars*	Species
	Soya bean	*Glycine max*	Species
Perennial forbs	Cup plant	*Silphium perfoliatum*	Species
	Red clover	*Trifolium pratense*	Use
	Sida / Virginia fanpetals	*Sida Hermaphrodita*	Species
Tall grasses	Arundo/ Giant cane/ giant reed	*Arundo (donax)*	Species
	Reed canary grass	*Phalaris arundinacea*	Use*
	Switchgrass	*Panicum virgatum*	Species
Small grasses (perennial)	High sugar grasses	*Mixed grasses*	Use
	Festulolium	*Lolium x fescue*	Use*
	Naked oat/ pillas	*Avena nuda*	Use**
	Perennial ryegrass	*Lolium perenne*	Use
Tree species	Alder	*Alnus glutinosa*	Use
	Black locust	*Robinia pseudoacacia,*	Species
	Eucalyptus	*Eucalyptus - (multiple species)*	Species
	Southern beech	*Nothofagus (43 species)*	Use
	Paulownia/ foxglove tree	*Paulownia*	Species
Shrubs	Prickly Acacia	*Vachellia nilotica*	Species
	Juniper	*Juniperus*	Species
Conservation biomass	Bracken	*Pteridium aquilinum*	Use
	Heather	*Calluna*	Use
	Hedge cuttings	*Mixed*	Use
	Biodiverse seed mixes for AD[3] feedstocks	*Mixed*	Use
Other	Sphagnum	*Sphagnum*	Species & Use***

* Seeds of festulolium and reed canary grass are commercially available, festulolium is grown as grazing or silage grass but there is only a limited number of varieties, similar RCG is grown for fodder or as game cover, in both cases cropping for biomass may involve different varieties or management which could be deemed to fit more within the novel species classification.
** Naked oats is a commercial crop grown for human consumption but there are a limited number of seed suppliers and growers, thus cropping for biomass could have a large impact on the planted area.
***Sphagnum moss is native to the UK and harvesting of "wild" moss does occur in the UK and Europe mainly for use in horticultural, but commercial cultivation of this crop is at very early stages in Europe[4].

[3] Anaerobic digestion
[4] Wichmann, S., et al. (2020). "Paludiculture on former bog grassland: Profitability of Sphagnum farming in Northwest Germany." Mires and Peat 26: 1-18.

Part 2 - What do we need to know about novel biomass crops?

Participants identified the key pieces of information that would enable the community to select, sustainably deploy, and utilise suitable novel biomass crops within the UK. For example, what are the questions growers need to ask to enable them to work with these crops, what questions would policymakers want to understand in order to consider supporting deployment, and what might an end user need to know to determine whether this crop could be of use for material or energy production. After the workshop, duplicate or similar comments were combined, resulting in 30 overarching information needs grouped into nine categories (Table 2).

Table 2: Information needed for novel biomass crops.

Category	Information needs
Readiness level	Availability of planting material in the UK Agricultural machinery required/available Level/depth of agronomic knowledge Existence of breeding programmes
Physiological range	Geographical range - which regions of the UK are suitable? Growth conditions (e.g., soil types) Tolerance to extremes (e.g., heatwaves)
Agronomy	Expected yields Cultivation Water and nutrient requirements Harvesting window Crop removal methods
Crop economics	Cost to establish and maintain Gross margin Volatility of end market price Current and future markets
Added value	Opportunities for carbon payments Likelihood of Government support (e.g., through ELMS/SFI/SFS[5]) Potential side revenue (e.g., honey production)
Feedstock quality	Moisture content Density Flammability in storage Composition and consistency Processing required
Environmental impacts	Carbon sequestration potential Biodiversity impacts Invasiveness Flammability - wildfires Provision/risk to ecosystem services
Policy	Political and Public acceptability

[5] Environmental Land Manager Scheme (ELMS) is the overarching scheme covering England, which provides payments to landowners for actions that aid environmental protection or recovery. The Sustainable Farming Incentive (SFI) is one part of this scheme. The Sustainable Farming Scheme (SFS) is the Welsh payment scheme for landowners carrying out similar sustainable actions.

Many of the points raised have multiple implications. For example, crop yields are of interest to landowners because they have a direct impact on crop profitability, but they are also of interest to many researchers because yield impacts land use requirements and the magnitude of land use change associated with biomass production. The nature of the workshop did not allow us to capture the nuance of the reasoning behind the suggestions, but the selection of a wider range of stakeholders was specifically designed to capture the full scope of the information required.

Readiness level

Comments focused on the need to understand the readiness level of novel biomass crops for deployment at scale in the UK. The discussions highlighted that this information is of interest to multiple stakeholder groups. Policymakers, industry, and researchers require this knowledge to predict the timescale over which large-scale deployment could be achieved and the level and nature of support that may be needed to achieve this. For landowners, such information is critical in being able to assess the availability of support and the level of risk.

Participants noted that the availability of planting material in the UK is critical for any scale up, as is an understanding of the nature and availability of agronomic machinery, especially if bespoke machinery is required. The existence of breeding programmes, in either the UK or internationally, was considered important in ensuring a crop's long-term viability in the face of climate change and emerging pests and diseases. Access to individuals' first-hand "tacit" knowledge and experience of crop cultivation and use was seen as being key in the ability to tackle unforeseen challenges with the establishment, growth, harvesting or utilisation of novel biomass crops.

Physiological range and agronomy

Comments focused on the question of where and how novel biomass crops could be grown. Policymakers, researchers, and industrialists all highlighted the desire for knowledge in this area, as these factors are critical in understanding the likely deployment pattern across the UK. The information encompassed not just the geographical (large scale) and physiological constraints (localised) but also a need to understand crop agronomy. Comments and discussion noted that crop agronomy will influence the acceptability of crops to different farming sectors, with lower barriers faced by crops which are complimentary to current practices. Comments on physiological range and crop agronomy noted that tolerance of extreme weather events will be important characteristics for novel biomass crops due to the changing climate, with specific reference made to water use and the impact of heatwaves and drought.

Crop economics and added value

Information regarding the potential breakeven points and gross margins were seen as fundamental to understanding the likely commercial success of novel biomass crops. As many novel biomass crops are perennial, an understanding of potential market volatility was also noted as a key information need, as was an understanding of the scale, nature, and location of current and future markets, as this will influence optimal crop deployment patterns. Linked to crop economics were requests for information on potential added value, either through subsidies, side revenues, or the opportunity to access payments for carbon sequestration.

Feedstock quality

Comments explored the suitability of the feedstock for different end uses. Both the composition and the consistency of the feedstock were considered important, especially with a view to the production of high-value materials. Potential flammability of the crop in storage was also noted, as was information needed about the level of processing required to make the biomass suitable for different end uses.

Environmental impact

Comments related to the need for information on a range of ecosystem services, with impacts on flooding, water availability and quality, nitrate leaching, and social impact were mentioned, in addition to several references to carbon sequestration and biodiversity. Questions on the risk of invasiveness of novel biomass crops were brought up by every breakout group highlighting the relevance of this question to multiple different stakeholders. As well as noting the importance of information on environmental impacts to ensure crops are produced sustainably, participants linked the need for information on environmental impacts to political and public acceptability and the marketability of the crop to landowners.

Policy

The final category of information needs related to the political and public acceptability of novel biomass crops. These two questions noted the need to understand the interaction between the potential scale of land-use change and the public and political response. These relate to an important point that was also brought up in the wider discussions: novel biomass crops, because they are new to the UK, are sensitive to public and political opinions and, actions or inaction from government could result in the stalling of any deployment. Licensing of hemp was highlighted as an example of a crop where deployment has been directly influenced by political decision-making.

Part 3 – What information do we already have on novel biomass crops?

In this workshop session, participants were asked to work in groups to use their own knowledge and expertise to fill out a table of questions on selected novel crop species. The input from part 2 (i.e., the key information needed for the consideration of novel biomass crops) was used to inform the following list of questions/topics to be addressed:

- Basic description of the crop (e.g., is it an annual or perennial, grass, tree, etc)
- Where can it grow?
- Is it grown in the UK?
- What is the yield or breakeven point?
- Key agronomy – how is it grown? (e.g., how and when is it established, how long does it live, when is it harvested)
- How easy is it to remove?
- What are the possible/current end uses?
- Nature/quality of the feedstock (density, moisture content etc)?
- What are the environmental concerns/benefits?
- Any opportunities for co-benefits or payments?
- Who is involved with these crops in the UK?

Participants were free to self-select into groups based on their common interests and expertise and some moved between groups at different points of the discussion. Groups chose novel crop species from the list compiled in part 1 of the workshop based on those they had the most knowledge of. Across four groups, the following crops were discussed:

- Group 1: Energy grasses, which the group split into two classes: Medium tall grasses such as Reed Canary Grasses and short grasses such as perennial Ryegrass (Miscanthus also used as a comparator but is not included in this summary)
- Group 2: Black locust and Eucalyptus species
- Group 3: Cup plant and Paulownia
- Group 4: Hemp and Sphagnum Moss

Not every question in the table was answered for every crop during the workshop. Several groups also added information on the potential impact of future climate change, although this was not originally included as a table heading.

Input gathered during this session of the workshop included both written submissions of information on sticky notes and references to specific websites and scientific literature, and the introductory presentations from crop specialists earlier in the workshop. Information drawn from all these sources was combined to produce Table 3 (a combined table can be found in the Appendix). Where key individuals were named, a draft version of this table was also sent to them to gather any additional comments, and to highlight any omissions.

Information in Table 3 is therefore from mixed sources, including first-hand reports and anecdotal evidence. Where used, links to published source material are provided, but neither statements nor the source material have been independently verified by the authors. In some cases, peer-reviewed scientific publications were provided as references by participants, and these are included as references. The information in Table 3 is a summary of data collected within the workshop. It is not intended to provide a detailed evidence review for comparison of the crops but as a basis for additional discussion and research.

The information provided shows that crops differ in their agronomic needs, the nature of the feedstocks produced, and potential environmental impacts (Table 3). This highlights the need to consider multiple factors in the decision-making process. Most of the crops were not limited to specific regions of the UK but had specific needs, such as a preference for free draining soil, which would result in localised rather than regional restrictions in deployment. Whilst direct combustion or the use in AD was an option for most of the crops, many have multiple potential end uses, including the production or co-production of non-energy products. This needs to be considered in any economic assessments or in the modelling of optimal deployment patterns across the UK landscape (Table 3).

The main limitations in the information known to participants was associated with the potential impacts of future climates on crop yields, and the environmental impacts of large-scale production on biodiversity and other system services such as soil health, and carbon sequestration (Table 3).

Much of the data provided was also anecdotal or reported only in grey literature with limited or no independent verification and insufficient details to make an assessment of the quality of the information. This is to be expected, given these are novel biomass crops, but it does highlight the need for more independent research and/or verification. The session did identify several commercial scale trials within the UK. Whilst small in number, and not available for all crops, these trials provide potential opportunities for the research community to work with industry to gather and independently verify additional data. Such a collaboration could support the expansion of data collection and facilitate the utilisation of researchers' modelling capability to address questions related to the impact of large-scale crop deployment on a number of ecosystem services.

The table also noted the potential benefits provided by novel biomass crops. Several of the crops listed are expected to be tolerant of future climate change and extreme weather. The diversity of potential crops, spanning annual to perennial plants, as well as new tree species, provides additional opportunities to integrate biomass cropping into current farming and forestry practices. Participants also noted that several of the crops have the potential to provide additional ecosystem services, as well as multiple end products. Commercial stakeholders also suggested that whilst invasiveness is a risk for some crops, this could be controlled through plantation management. There was also a recognition and an openness towards the need for research and the development of monitoring and verification processes to help realise these benefits.

Table 3: Information on novel biomass crops provided by workshop participants.
This table is split into separate parts on the following pages, but a full table can be found in the appendix. This table is intended only as a summary of the information collected within the workshop, not as a detailed evidence review. The information contained within this table originates from workshop participants, drawing on their first-hand knowledge and in some cases published material. Unless peer-reviewed literature is cited, it does not contain independently verified scientific information.

Crop	Small energy grasses
Description	Perennial C3 grass, forage grasses, low growing (under 1m) grass. e.g., Perennial ryegrass/Timothy Harvested wet/green, with multiple cuts per year. Fields are normally reseeded every ~5 years.
Where in the UK could it grow?	UK-wide, on a wide range of soil conditions.
Currently grown in the UK?	Yes, commercially. Widely grown commercially as animal fodder. Examples of growth for biomass were not known by attendees, but management for this purpose was not expected to differ from current practice.
Yield/break-even points	20 t ha wet, 12 - 13 t DM in the UK. Multiple cuts per year are possible.
Key agronomy considerations	Established from seeds and managed as per silage. Very familiar to landowners and uses conventional machinery. Up to two cuts per year. Inputs (fertiliser) are needed to maximize production when planted in a pure mix (100- 300kg N/Yr) although mixing grasses with legumes can reduce or eliminate the need for nitrogen fertilisers.
Removal	Removal is achieved using herbicides and tillage.
Future climates	Increased threat especially from disease.
Possible end uses	Silage, AD, or fermentation processes (e.g., ethanol production).
Feedstock quality	Grasses in comparison to woody crops have less lignin and greater amounts of cellulose, hemicellulose, and ash. High sugar varieties best suited for AD. Produces a “wet” crop best used locally (due to the cost of transporting).
Environmental considerations	Evidence from conventional uses that these crops can increase soil carbon. These crops require higher inputs (fertiliser) than alternative “energy grasses” such as Switchgrass and Miscanthus, but lower levels than alternative AD feedstocks such as maize. Reduced erosion risk compared to annual crops such as maize.
Co-benefits /payments	Opportunities plus threats for carbon credits.
References or other sources of information	No information provided.

Crop	Medium to tall energy grasses
Description	Perennial C3/C4 grasses, medium to tall (1-6 m), e.g. Reed Canary Grass (RCG), Arundo donax and switchgrass. Harvested yearly wet or dry. Life span 7 – 15 years depending on species and management.
Where in the UK could it grow?	UK wide depending on species. Specific conditions will depend on species/varieties but can grow low nutrient soils, flood plains, and non-agricultural marginal lands such as capped landfills, restored mine lands, and abandoned grazing land. Arundo is also salt tolerant and can grow on saline soils[12].
Currently grown in the UK?	Yes. UK planting specifically for biomass is currently limited to experimental plots/ trials. RCG is also grown, under different management, as forage and game cover. UK trail sites include the 8 Biomass Connect sites, Knoydart NW Scotland, mine sites in Wales, NE England and SW Scotland, and at 5 brownfield sites (see BioReGen project).
Yield/break-even points	5- 10 t DM/ha in the UK, from year 2 for RCG in the USA Arundo and switchgrass yields higher than RGC (by factors of 2-4) but potential yields in UK conditions requires research.
Key agronomy considerations	All species are established from seeds and harvested and planted using conventional machinery. Most take 2-3 years to fully establish. RCG is a low input crop, harvested late summer until early spring depending on if a wet or dry crop is required. Tolerates a wide range of management including grazing, and irregular harvesting. Will grow on wetlands and riparian zones, but also in drier areas.
Removal	Reversibility is proven but uses glyphosates. It is unclear how removal will be achieved without this herbicide[13].
Future climates	Theoretically, these grasses are expected to be tolerant to climate change e.g., RCG is well adapted to warmer winters, and is tolerant to dry periods.
Possible end uses	AD, combustion, animal bedding, pulp, and paper production. Research is underway into building materials, packing, chemicals, ethanol, and bioplastics.
Feedstock quality	In comparison to woody crops, grasses have less lignin and greater amounts of cellulose, and hemicellulose but the higher ash and alkali metal content. This metal content and lower ash fusion temperatures may be an issue for combustion.
Environmental considerations	Soil carbon increases: There is limited data for RCG, and for switch grass evidence is available but for USA only. Phytoremediation: empirical evidence of RGC outperforming Miscanthus and SRC willow on contaminated soils in the UK[14]. Flood mitigation, soil erosion /nitrate mitigation and phosphate management: benefits expected but evidence is anecdotal. Biodiversity impacts: mostly for ornithology, some evidence of benefits depending on species[15]. Water management: limited evidence, anecdotal evidence of lodging.
Co-benefits /payments	Opportunities plus threats for carbon credits.
References or other sources of information	[12] Arundo Crop Information, Biomass Connect [13] Mangold, A., et al. (2019). "How can miscanthus fields be reintegrated into a crop rotation?" GCB Bioenergy **11**(11): 1348-1360. [14] Lord, R. A. (2015). "Reed canary grass () outperforms Miscanthus or willow on marginal soils, brownfield and non-agricultural sites for local, sustainable energy crop production." Biomass and Bioenergy 78: 110-125. [15] Kirsch, E., et al. (2007). "Breeding bird territory placement in riparian wet meadows in relation to invasive reed canary grass, Phalaris arundinacea." Wetlands 27: 644–655. Additional information: Workshop presentation slides from Elaine Jensen. For RCG phytoremediation information, contact Richard.lord@strath.ac.uk.

Crop	Black locust
Description	North American, nitrogen fixing, deciduous tree. Noted for abundant flowering. Can be coppiced or grown as single stem. Single stem stands reach maturity at ~15 yrs. Can regrow without re-planting.
Where in the UK could it grow?	Not restricted to specific regions but prefers sandy soil and requires a low ground water table. For Turbo Obelisk® variety: Minimum 300+ mm rainfall, pH < 9, Total salt content (salinity) < 0,05%, $CaCO_3$ content at or below 15% [16].
Currently grown in the UK?	Yes, at trial sites only. Currently known trials are located at the 8 Biomass Connect sites. These were planted in spring 2023, with an additional older plantation also hosted at the Biomass Connect BGI site.
Yield/break-even points	Turbo Obelisk® cultivator, expected yields based on EU data: 15 dry t/ha/yr when coppiced for biomass, 20 dry t/ha/yr (400m^3/ha in total) when grown on a 12–15-year rotation period giving a mix of timber products and lower grade wood suited for biomass[16].
Key agronomy considerations	Planted as saplings. Harvested using conventional forestry machinery or manually grown as coppice or as single stem. Single stem crop is thinned at 6-7 yrs., for pole wood, then clear felled at 15 years for timber. Coppiced crop is harvested every 3 years. When grown for timber, it shouldn't be allowed to regrow from stumps as this leads to lower quality, but fields can be tilled and allowed to regrow from roots meaning replanting is not required. No fertiliser of irrigation requirements (not even trace elements). Harvest winter November-February. Supply of planting material is not an issue as suppliers can produce planting for 100s of ha at short notice.
Removal	Removal is achieved using herbicides. Trees will regrow readily from roots so removal must be carefully managed to ensure crop removal is effective.
Future climates	Black locust is grown commercially over a large geographical area so is expected to be tolerant of climate change impacts in the UK.
Possible end uses	Combustion and timber. Pole wood is currently the main end use rather than biomass.
Feedstock quality	High levels of natural tannins, which can be undesirable for end-users. Levels are lower in younger/coppiced material. 40% moisture content when cut. Density 740 kg/m3 oven dry[16].
Environmental considerations	Potential risk of invasiveness: Not invasive from seeds but can spread via roots. This can be controlled by cultivation between rows and on the outside of the crop. Biodiversity impacts require research: Black locusts flower profusely, thus there is an expected value for pollinators. Impacts on erosion and soil carbon requires research and will need to include impacts of management of the understory.
Co-benefits /payments	Honey production.
References or other sources of information	[16] Workshop presentation slides from Marton Nemeth

Crop	Eucalyptus
Description	Australian evergreen tree. Selected for rapid growth. Can be coppiced or grown as single stem. Single stem stands reach maturity at ~10 yrs. regrows without re-planting.
Where in the UK could it grow?	Potentially UK wide but requires careful selection of variety/species to match local conditions. Highest yields in southern UK. Some locations will be unsuitable, due to specific conditions (e. g. frost pockets, high exposure), but this is localised rather than regional.
Currently grown in the UK?	Yes, commercially and at trial sites. UK commercial sites located across mainland UK in Ayrshire, Moray, Windsor, Cornwall, Devon, and Derbyshire, Additional trial plots at the 8 Biomass Connect sites, and Forestry Research sites.
Yield/break-even points	Potential of 40 m^3/ha/yr. 2-3m height gain a year.
Key agronomy considerations	Planted as saplings. Harvested using conventional forestry machinery or manually. Grown as coppice or as single stem. Single stem crop is clear felled at 8 – 10 yrs. Coppiced crop is harvested every 3 yrs. Trees can regenerate from stumps for single stem crops. Recommended practice is to remove all but one regenerating shoot to produce more valuable timber. Highly productive but frost tolerance, water, light and soil type requirements vary greatly between varieties. It is essential to choose the correct variety for each project on a site-by-site basis. Spreading roots of crops can limit use in agroforestry systems.
Removal	No information provided.
Future climates	Theoretically, milder winters and warmer temperatures may favour Eucalyptus cultivation.
Possible end uses	Combustion, timber including saw logs.
Feedstock quality	Wood has high moisture content so requires drying.
Environmental considerations	Concerns of potential negative impacts on soil microbiome due to allopathic chemicals but limited data. Invasiveness is unknown but expected to be unlikely in commercial systems. Understory plants can develop increasing biodiversity value. Stressed trees will however shed both leaves and bark reducing understory diversity. Matching of varieties to local conditions is therefore critical to limit leaf drop. Risk of emission of volatiles, which can affect air quality; the impact will depend on local conditions.
Co-benefits /payments	Potential use of foliage in floristry and production of essential oils.
References or other sources of information	Additional information: Eucalyptus Renewables

Crop	**Paulownia**
Description	Sterile hybrids of an Asian deciduous hardwood tree. Can be coppiced but most often grown as a single stem. Single stem stands reach maturity at ~15 yrs. Can regrow without re-planting.
Where in the UK could it grow?	Unclear but will be restricted to areas with high rainfall or where irrigated can be provided due to high water requirements. Areas exposed to high winds are also unsuitable, due to the risk of leaf damage.
Currently grown in the UK?	Yes, at four approved commercial scale pilots: Euston Estate Suffolk (486 ha), South Pickenham, West Acre and Rutterfore Estates in Norfolk.
Yield/break-even points	Yields are unknown/unpublished for the UK.
Key agronomy considerations	Planted as saplings. Harvested using conventional forestry machinery or manually. Grown as a single stem or coppiced (depending on variety). Trees can regenerate from stumps. For single stem crops recommended practice is to remove all but one stem to produce more valuable timber but can alternatively be grown as a multi stem coppice. UK trial will be thinning at 6-7 years with remaining trees cut at 12-14 years [17]. It is unclear if cut trees will be replanted or all to regrow from stumps. The growth of sterile hybrids is recommended to avoid invasion risks and for higher yields. UK trials are using the "Phoenix One" fast-growing hybrid. Requires irrigation during establishment, and continued irrigation in areas where rainfall is below 100mm per month (see Biotree).
Removal	No information provided
Future climates	No information provided
Possible end uses	Combustion, ethanol, timber. The international market for the timber could compete with lower value bulk biomass sectors.
Feedstock quality	No information provided.
Environmental considerations	Carbon dynamics are unknown. Risks around importing foreign diseases. Biodiversity impacts require research. Species have the potential to be invasive if allowed to seed. Seeding could be avoided through sterile hybrids. The need for irrigation during establishment could pose a risk in areas with limited water resources.
Co-benefits /payments	Leaves can be harvested for browsing.
References or other sources of information	[17] Environmental Statement, Carbon Plantations Ltd. J S Young. Additional information: WeGrow Pheonix One, BIO TREE company

Crop	Cup plant
Description	North American perennial flowering forb. 1-3 m tall. Harvested yearly. Productive for up to 15 years.
Where in the UK could it grow?	Not restricted to specific regions, but best in area with wet soil/high rainfall. Widely grown in Germany and can grow on marginal soils. Well suited to Scotland and Ireland, where maize, the alternative crop, does not perform well.
Currently grown in the UK?	Yes, at pilot scale. Field scale trials are ongoing in Kent, Lincoln, South Wales, and Ireland.
Yield/break-even points	Limited UK data as trials have only just started. Field trial in Kent yield 15 t DM/ha, Ireland trial failed.
Key agronomy considerations	Established from seed. Harvested and planted using conventional machinery. Takes 3 years to fully establish but in year 1 it can be seeded as a companion crop to maize. Once established is expected to be productive for up to 15 years. Weed control is required in year 1, but the crop will shade out weeds after this. Harvested yearly September-October as a green crop. Can be difficult to establish. In the UK, seed is expensive and suppliers are limited. Fertiliser requirements are similar to maize: Will depend on yield but nutrient removed during harvest (crop-off take) are estimated to be: 150 – 250 kg of N/ha, 75 kg P/ha/year, and 165 kg K/ha/year. Nutrient needs can be met via the use of AD digestate.
Removal	Proven reversibility in Germany.
Future climates	No information provided
Possible end uses	Primary end use is AD, as well as animal fodder. AD up to 100% feed-in rate and methane yield in AD 290 l/kg DM. If used at 100% feed-in rate in AD systems the resulting high fibre digestate can be used to make paper.
Feedstock quality	High in both sugar and fibre with higher protein content than maize. Well suited for AD.
Environmental considerations	Soil carbon: Increases in below ground carbon of 5-8 t CO_2 /ha/year reported. In Germany, payments for carbon credits are available to growers. No known pests in the UK thus insecticides are not needed. Long flowering period provides potential benefits for pollinators, but data is anecdotal. Water quality, nitrogen leaching, biodiversity and opportunities for phytoremediation: benefits expected especially in comparison to the alternative crop of maize, but data is anecdotal. Potential for invasiveness, but anecdotal evidence suggests low risk. Seeds have low germination rates, and roots are intolerant of transplantation.
Co-benefits /payments	Carbon trading, paper production and potential honey production. Co-production of fodder and biomass possible with multiple cuts per year.
References or other sources of information	Additional information: Carbocert in Germany is facilitating the trading of carbon credits. Workshop presentation slides from Tim Wood.

Crop	Hemp
Description	Annual flowering forb with multiple varieties. Re-sown yearly, grown in rotation with arable crops. Grown for fibre or seed, occasionally for both. Fibre varieties have the highest bulk biomass yield and grow 2-3 m tall.
Where in the UK could it grow?	On arable lands UK wide, prefers nutrient and organic rich soils, but can grow on lighter free draining soils. Grows best on neutral to slightly alkaline soils. Planting licence is required.
Currently grown in the UK?	Yes, commercially at small scale, and trial plots. 20 farms in the UK growing ~800 ha. Definite interest in expansion. Trial plots at NIAB and in Aberystwyth. Seeds are currently difficult to access due to a lack of UK source.
Yield/break-even points	Range of reported yield for the UK: 5.5 – 8 t/ ha. [18] Variety trail at Aberystwyth: 4.1 - 15.9 t DM /ha in 2021, 7.4 - 17.6 t DM/ha. Potential gross margin of £600-900 if seed and fibre can be processed and sold to onward markets, with residues (straw, shives) sold for biomass.
Key agronomy considerations	Established from seed. Conventional machinery suitable for planting, but not ideal for harvesting. Management and harvesting will depend on whether seed or fibre is the primary product. Specialist harvesting machinery is available, but costly. In some cases, conventional equipment can be used. Low water requirement, 630 – 750 mm/yr., 200-300 mm during growth. Sown late March early May. Matures in ~100 days, tolerant of high temperatures, not very tolerant of water logging in the lower root zones. Can be cultivated on light and nutrient-poor soil with appropriate fertilisation. Fertiliser ranges between 80 –190kg N/ha, 90 -175kg K/ha, 50 - 67kg P /ha. depending on soil fertility. No post-sowing herbicide but does require a weed-free seedbed at planting.
Removal	Proven reversibility, but volunteers (limited regrow from drop seeds) possible in the following season.
Future climates	Grown widely in Europe, will adapt to local conditions if successive generations of seed are saved.
Possible end uses	Combustion, AD, ethanol, biodiesel, construction material, fibres, oil. Greatest value is in the utilisation of the fibre/seed, with energy as a co-product.
Feedstock quality	Higher concentration of digestible cellulose and hemicellulose than other energy crops such as willow and energy grasses. Blast fibre: 73-77% cellulose, 7-9% hemicelluloses, 2-6% lignin, Hurd: 48%, 21-25%, 17-19% respectively.
Environmental considerations	Susceptibility to wildfires needs to be considered. Reduced chemical usage: Does not require herbicide or pesticide during growth, can also reduce weeds and nematode pests' growth in the following crop. Can remove heavy metals from polluted soil. Wind pollinated but can provide a pollen source for pollinators. Anecdotal evidence for soil carbon sequestration: In addition to the conversion of the harvested biomass into long-lived materials, roots and leaves are expected to add between 1.68 – 2.45 CO_2/ha/yr to soils (based on the yield of 5.5 – 8 t ha) (calculated based on values from[18]) but long-term stability of this material is unknown.
Co-benefits /payments	Production of multiple products from a single crop. USA (Kentucky) and S. Australia reported a yield uplift of 10-20% in winter wheat after hemp.
References or other sources of information	[18] Hemp Review: Industrial Hemp Cultivation in the UK, (2023). Additional information: Biomass Connect, Hemp as a Biomass Crop, 2023. H. Blandinières, et al. Multi-environment assessment of a yellow hemp (Cannabis sativa L.) cultivar's eco-physiology and productivity under varying levels of

Crop	**Sphagnum moss**
Description	Perennial moss, grown under a high-water table (5 cm below surface), or with overhead irrigation [19]. Potential as biomass feedstock is unclear.
Where in the UK could it grow?	Not restricted to specific regions but requires high water table or irrigation. Best suited to degraded peatlands, where production can be combined with peatland restoration [19,20,21].
Currently grown in the UK?	Yes, at trial scale, and wild. Fens for the Future has conducted trials to explore commercial production methods at two sites in Greater Manchester and Leicestershire.
Yield/break-even points	No information provided.
Key agronomy considerations	Established as plugs. Require specialised harvest machinery, small-scale production can use manual harvesting. Area must have a high-water table or irrigation.
Removal	No information provided.
Future climates	No information provided.
Possible end uses	Value as biomass feedstock unclear. Although has been used as a fuel, it is unlikely to be profitable as a bulk energy crop but may have value as a biomaterial. A potential end market is the production of peat-free compost, with 50 million tonnes of compost expected to be required per annum.
Feedstock quality	No information provided.
Environmental considerations	Potential benefits for biodiversity, soil carbon, soil health, water quality and phytoremediation.
Co-benefits /payments	Sphagnum farming may provide a mechanism to allow peat restoration whilst still providing income to landowners.
References or other sources of information	[19] Beadamoss [20] Fens for the Future [21] Strathclyde University – growing sphagnum to replace peat Additional information: G. Gaudig, Sphagnum farming from species selection to the production of growing media: a review, Mires and Peat 20 (2018) 1-30.
	nitrogen fertilisation, Industrial Crops and Products 195 (2023).Workshop presentation slides from Alan Gay.

Part 4 - Where is further research needed?

The workshop participants were asked to consider the knowledge gaps that they had identified for the novel biomass crops discussed and use these to reflect on critical research needs. The research needs identified by participants varied between crops. Though often very crop specific, seven distinct themes were identified:

- Agronomic trials e.g., Trials to aid in optimising crop management, or to test the capacity of crops to tolerate a range of conditions, including contaminated soils. Trials were also seen as playing a role in removing barriers to scale-up by providing stakeholders, including landowners, an opportunity to see crops in situ.
- Assessment of ecosystem services impacts, e.g., the independent assessments of the impacts of crop production on a range of ecosystem services including biodiversity, water quality, carbon dynamics and permanency. Exploration of opportunities for phytoremediation, and the risk of importing new tree diseases, or invasiveness of the crops.
- Impacts of future climates – e.g., the need to understand tolerances to weather extremes (e.g., flooding events or heat waves) and future climates.
- Exploring new end uses and markets. e.g., the development of new construction materials such as "hempcrete".
- Development of crop production techniques or machinery – e.g., improved harvest machinery for new crops, propagation method with lower cost and energy requirements.
- Crop breeding for improved traits e.g., the need to improve growth traits of native tree species to expand their use.
- Pathways for scaling up deployment e.g., developing a strategic plan to ensure the supply of and demand for novel biomass crops by ensuring links between the production of planting material, landowners, and end users.

These research needs are reflected in table 3. The limited number and scale of UK trials are evident, as is the absence or theoretical nature of information on the impact of future climates. There are also a number of references to the need for research due to anecdotal nature of the information currently held on the potential environmental benefits of crops, such as the potential pollinator benefits of Black Locust.

These research needs also closely follow the programmes that have been funded within the Biomass Feedstock Innovation Programme. This programme includes the UK-wide demonstrator platform and information hub Biomass Connect, as well as projects developing new harvest machinery (Net Zero Willow, White Horse Energy), methods for low-cost propagation (TEMPEC, Taeda Tech), new breeding programmes (Miscanspeed, AWBD) and systems to support scale up (OMENZ, EnviroCrops, Bioforce). This overlap highlight the crop agnostic nature of some of the research needs identified, research and technological advances in these areas being fundamental for the successful large-scale deployment of any biomass crop. Biomass Connect trials, however, do not cover the full scope of novel biomass crops identified within this workshop. For example, whilst Black Locust is being grown within the network of demonstration sites, Paulownia and Cup Plant are not being studied. The novel crop trials within these sites are also small-scale and are only funded for a few years, thus they are unable to address questions on the ecosystem services impacts of large-scale commercial deployment, and they are not long enough to address questions around the scale or permanency of carbon sequestration.

Conclusion

The novel biomass crops identified within this workshop provide opportunities for the UK biomass industry. Their diversity and contrasting agronomic needs mean they could dramatically expand the “toolbox” of crops available to the sector, and some have additional benefits such as potential tolerance to climate change or provision of ecosystem services.

This workshop showed there is already a level of knowledge about both the potential benefits and risks of many novel biomass crops, and an understanding of which questions will need to be addressed before large-scale crop deployment. UK trials are widely seen as being invaluable in addressing outstanding questions around the performance of these crops under UK conditions and the potential wider implications for ecosystem services and natural capital.

Fundamental to the development of novel biomass crops is the quantification and management of the risks and benefits of novel crop deployment. Within this context, our workshop highlighted the need for independent verification of current data and additional research, especially related to crop breeding and the assessment of the impact of novel biomass crops on biodiversity, soil health and social carbon sequestration. Partnerships between industry, researchers and policymakers will be critical in delivering this research. We hope that the connections made within this workshop will help to facilitate this process.

Appendix

Table 3 full version: Information on novel biomass crops provided by workshop participants from the Supergen Bioenergy Hub Stakeholder Workshop on Novel Crops and Forestry Species as Sources of Industrial Biomass. This table is intended only as a summary of the information collected within the workshop, not as a detailed evidence review. The information contained within this table originates from workshop participants, drawing on their first-hand knowledge and in some cases published material. Unless peer reviewed literature is cited it does not contain independently verified scientific information.

Crop	Small Energy Grasses	Medium to tall energy grasses	Black Locust	Eucalyptus
Description	Perennial C3 grass, forage grasses, low growing (under 1m) grass. e.g., Perennial ryegrass/Timothy. Harvested wet/green, with multiple cuts per year. Fields are normally reseeded every ~5 years.	Perennial C3/C4 grasses, medium to tall (1-6 m), e.g. Reed Canary Grass (RCG), Arundo donax and switchgrass. Harvested yearly wet or dry. Life span 7 – 15 years depending on species and management.	North American, nitrogen fixing, deciduous tree. Noted for abundant flowering. Can be coppiced or grown as single stem. Single stem stands reach maturity at ~15 yrs. Can regrow without re-planting	Australian, evergreen tree. Selected for rapid growth. Can be coppiced or grown as single stem. Single stem stands reach maturity at ~10 yrs. regrows without re-planting.
Where in the UK could it grow?	UK-wide, on a wide range of soil conditions.	UK wide depending on species. Specific conditions will depend on species/varieties but can grow low nutrient soils, flood plains, and non-agricultural marginal lands such as capped landfills, restored mine lands, and abandoned grazing land. Arundo is also salt tolerant and can grow on saline soils (1).	Not restricted to specific regions but prefers sandy soil and requires a low ground water table. For Turbo Obelisk® variety: Minimum 300+ mm rainfall, pH < 9, Total salt content (salinity) < 0,05%, CaCO3 content at or below 15% 16.	Potentially UK wide but requires careful selection of variety/species to match local conditions. Highest yields in Southern UK. Some locations will be unsuitable, due to specific conditions (e. g. frost pockets, high exposure), but this is localised rather than regional.
Currently grown in the UK?	Yes, commercially. Widely grown commercially as animal fodder. Examples of growth for biomass were not known by attendees, but management for this purpose was not expected to differ from current practice	Yes. UK planting specifically for biomass is currently limited to experimental plots/ trials. RCG is also grown, under different management, as forage and game cover. UK trail sites include the eight Biomass Connect sites, Knoydart NW Scotland, mine sites in Wales, NE England and SW Scotland, and at five brownfield sites (see BioReGen project).	Yes, at trial sites only. Currently known trials are located at the eight Biomass Connect sites. These were planted in spring 2023, with an additional older plantation also hosted at the Biomass Connect BGI site.	Yes, commercially and at trial sites. UK commercial sites located across mainland UK in Ayrshire, Moray, Windsor, Cornwall, Devon and Derbyshire, Additional trial plots at the eight Biomass Connect sites, and Forestry Research sites.
Yield/break-even points	20 t ha wet, 12 - 13 t DM in the UK. Multiple cuts per year are possible.	5- 10 t DM/ha in the UK, from year 2 for RCG in the USA Arundo and switchgrass yields higher than RGC (by factors of 2-4) but potential yields in UK conditions requires research.	Turbo Obelisk® cultivator, expected yields based on EU data: 15 dry t/ha/yr when coppiced for biomass, 20 dry t/ha/yr (400m3/ha in total) when grown on a 12–15-year rotation period giving a mix of timber products & lower grade wood suited for biomass (5).	Potential of 40 m3/ha/yr. 2-3m height gain a year.
Key agronomy considerations	Established from seeds and managed as per silage. Very familiar to landowners and uses conventional machinery. Up to two cuts per year. Inputs (fertiliser) are needed to maximize production when planted in a pure mix (100- 300kg N/Yr) although mixing grasses with legumes can reduce or eliminate the need for nitrogen fertilisers.	All species are established from seeds and harvested and planted using conventional machinery. Most take 2-3 years to fully establish. RCG is a low input crop, harvested late summer until early spring depending on if a wet or dry crop is required. Tolerates a wide range of management including grazing, and irregular harvesting. Will grow on wetlands and riparian zones, but also in drier areas.	Planted as saplings. Harvested using conventional forestry machinery or manually. Grown as coppice or as single stem. Single stem crop is thinned at 6-7 yrs., for pole wood, then clear felled at 15 years for timber. Coppiced crop is harvested every 3 years. When grown for timber, it shouldn't be allowed to regrow from stumps as this leads to lower quality, but fields can be tilled and allowed to regrow from roots meaning replanting is not required. No fertiliser of irrigation requirements (not even trace elements). Harvest winter Nov- Feb. Supply of planting material is not an issue as suppliers can produce planting for 100s of ha at short notice.	Planted as saplings. Harvested using conventional forestry machinery or manually. Grown as coppice or as single stem. Single stem crop is clear felled at 8 – 10 yrs. Coppiced crop is harvested every 3 yrs. Trees can regenerate from stumps for single stem crops. recommended practice is to remove all but one regenerating shoot to produce more valuable timber. Highly productive but frost tolerance, water, light and soil type requirements vary greatly between varieties. It is essential to choose the correct variety for each project on a site-by-site basis. Spreading roots of crops can limit use in agroforestry systems.
Removal	Removal is achieved using herbicides and tillage.	Reversibility is proven but uses glyphosates. It is unclear how removal will be achieved without this herbicide. (2)	Removal is achieved using herbicides. Trees will regrow readily from roots so removal must be carefully managed to ensure crop removal is effective.	No information provided.
Future climates	Increased threat especially from disease.	Theoretically, these grasses are expected to be tolerant to climate change e.g., RCG is well adapted to warmer winters, and is tolerant to dry periods.	Black locust is grown commercially over a large geographical area so is expected to be tolerant of climate change impacts in the UK.	Theoretically, milder winters and warmer temperatures may favour Eucalyptus cultivation.
Possible end uses	Silage, AD, or fermentation processes (e.g., ethanol production).	AD, combustion, animal bedding, pulp, and paper production. Research is underway into building materials, packing, chemicals, ethanol, and bioplastics.	Combustion and timber. Pole wood is currently the main end use rather than biomass.	Combustion, timber including saw logs.
Feedstock quality	Grasses in comparison to woody crops have less lignin and greater amounts of cellulose, hemicellulose, and ash. High sugar varieties best suited for AD. Produces a "wet" crop best used locally (due to the cost of transporting).	In comparison to woody crops, grasses have less lignin and greater amounts of cellulose, and hemicellulose but the higher ash and alkali metal content. This metal content and lower ash fusion temperatures may be an issue for combustion.	High levels of natural tannins, which can be undesirable for end-users. Levels are lower in younger/coppiced material. 40% moisture content when cut. Density 740 kg/m3 oven dry (5).	Wood has high moisture content so requires drying.
Environmental considerations	Evidence from conventional uses that these crops can increase soil carbon. These crops require higher inputs (fertiliser) than alternative "energy grasses" such as Switchgrass and Miscanthus, but lower levels than alternative AD feedstocks such as Maize. Reduced erosion risk compared to annual crops such as maize.	Soil carbon increases: There is limited data for RCG, and for switch grass evidence is available but for USA only. Phytoremediation: empirical evidence of RGC outperforming Miscanthus and SRC willow on contaminated soils in the UK (3). Flood mitigation, soil erosion /nitrate mitigation and phosphate management: benefits expected but evidence is anecdotal. Biodiversity impacts: mostly for ornithology, some evidence of benefits depending on species (4). Water management: limited evidence, anecdotal evidence of lodging.	Potential risk of invasiveness: Not invasive from seeds but can spread via roots. This can be controlled by cultivation between rows and on the outside of the crop. Biodiversity impacts require research: Black locusts flower profusely thus there is an expected value for pollinators. Impacts on erosion and soil carbon requires research and will need to include impacts of management of the understory.	Concerns of potential negative impacts on soil microbiome due to allopathic chemicals but limited data. Invasiveness is unknown but expected to be unlikely in commercial systems. Understory plants can develop increasing biodiversity value. Stressed trees will however, shed both leaves and bark reducing understory diversity. Matching of varies to local conditions is therefore critical to limited leaf drop. Risk of emission of volatiles, which can affect air quality, the impact will depend on local conditions.
Co-benefits/payments	Opportunities plus threats for carbon credits.	Opportunities plus threats for carbon credits.	Honey Production.	Potential use of foliage in floristry and production of essential oils.
References or other sources of information	No information provided.	(1) Arundo Crop Information, Biomass Connect (2) - Mangold, A., et al. (2019). "How can miscanthus fields be reintegrated into a crop rotation?" GCB Bioenergy 11(11): 1348-1360. (3) Lord, R. A. (2015). "Reed canary grass () outperforms Miscanthus or willow on marginal soils, brownfield and non-agricultural sites for local, sustainable energy crop production." Biomass and Bioenergy 78: 110-125. (4) Kirsch, E., et al. (2007). "Breeding bird territory placement in riparian wet meadows in relation to invasive reed canary grass, Phalaris arundinacea." Wetlands 27: 644–655. Additional information: Workshop presentation slides from Elaine Jensen. For RCG phytoremediation information contact :Richard.lord@strath.ac.uk.	(5) Workshop presentation slides from Marton Nemeth	Additional information: Eucalyptus Renewables

Crop	Paulownia	Cup Plant	Hemp	Sphagnum moss
Description	Sterile hybrids of an Asian deciduous hardwood tree. Can be coppiced but most often grown as a single stem. Single stem stands reach maturity at ~15 yrs. Can regrow without re-planting.	North American perennial flowering forb. 1-3 m tall. Harvested yearly. Productive for up to 15 years.	Annual flowering forb with multiple varieties. Re-sown yearly, grown in rotation with arable crops. Grown for fibre or seed, occasionally for both. Fibre varieties have the highest bulk biomass yield and grow 2-3 m tall.	Perennial, moss, grown under a high-water table (5 cm below surface), or with overhead irrigation (8) Potential as biomass feedstock is unclear.
Where in the UK could it grow?	Unclear but will be restricted to areas with high rainfall or where irrigated can be provided due to high water requirements. Areas exposed to high winds are also unsuitable, due to the risk of leaf damage.	Not restricted to specific regions, but best in area with wet soil/high rainfall. Widely grown in Germany and can grow on marginal soils. Well suited to Scotland and Ireland, where maize, the alternative crop, does not perform well.	On arable lands UK wide, prefers nutrient and organic rich soils, but can grow on lighter free draining soils. Grows best on neutral to slightly alkaline soils. Planting licence is required.	Not restricted to specific regions but requires high water table or irrigation. Best suited to degraded peatlands, where production can be combined with peatland restoration (8),(9), (10).
Currently grown in the UK?	Yes, at four commercial scale pilots approved: Euston Estate Suffolk (486 ha), South Pickenham, West acre and Rutterfore Estates in Norfolk.	Yes, at pilot scale. Field scale trials are ongoing in Kent, Lincoln, South Wales, and Ireland.	Yes, commercially at small scale, and trial plots. 20 farms in the UK growing ~800 ha. Definite interest in expansion. Trial plots at NIAB and in Aberystwyth. Seeds are currently difficult to access due to a lack of UK source	Yes- at trial scale, and wild. Fens for the Future has conducted trials to explore commercial production methods at two sites in Greater Manchester and Leicestershire.
Yield/break-even points	Yields are unknown/unpublished for the UK.	Limited UK data as trials have only just started. Field trial in Kent yield 15 t DM/ha, Ireland trail failed.	Range of reported yield for the UK: 5.5 – 8 t/ ha. (7) Variety trail at Aberystwyth: 4.1 - 15.9 t DM /ha in 2021, 7.4 - 17.6 t DM/ha. Potential gross margin of £600-900 if seed and fibre can be processed and sold to onward markets, with residues (straw, shives) sold for biomass.	No information provided
Key agronomy considerations	Planted as saplings Harvested using conventional forestry machinery or manually. Grown as a single stem or coppiced (depending on variety). Trees can regenerate from stumps, for single stem crops recommended practice is to remove all but one stem to produce more valuable timber but can alternatively be grown as a multi stem coppice. UK trial will be thinning at 6-7 years with remaining trees cut at 12-14 years (6). It is unclear if cut trees will be replanted or all to regrow from stumps. The growth of sterile hybrids is recommended to avoid invasion risks and for higher yields. UK trials are using the "Phoenix One" fast-growing hybrid. Requires irrigation during establishment, and continued irrigation in areas where rainfall is below 100mm per month (see Biotree).	Established from seed. Harvested and planted using conventional machinery. Takes 3 years to fully establish but in year 1 it can be seeded as a companion crop to maize. Once established is expected to be productive for up to 15 years. Weed control is required in year 1, but the crop will shade out weeds after this. Harvested yearly September-October as a green crop. Can be difficult to establish. In the UK, seed is expensive and suppliers are limited. Fertiliser requirements are similar to maize: Will depend on yield but nutrient removed during harvest (crop-off take) are estimated to be: 150 – 250 kg of N/ha, 75 kg P/ha/year, and 165 kg K/ha/year. Nutrient needs can be met via the use of AD digestate.	Established from seed. Conventional machinery suitable for planting, but not ideal for harvesting. Management and harvesting will depend on whether seed or fibre is the primary product. Specialist harvesting machinery is available, but costly. In some cases, conventional equipment can be used. Low water requirement, 630 – 750 mm/yr., 200-300 mm during growth. Sown late March early May. Matures in ~100 days, tolerant of high temperatures, not very tolerant of water logging in the lower root zones. Can be cultivated on light and nutrient-poor soil with appropriate fertilisation. Fertiliser ranges between 80 –190kg N/ha, 90 -175kg K/ha, 50 - 67kg P /ha. depending on soil fertility. No post sowing herbicide but does require a weed free seedbed at planting.	Established as plugs. Require specialised harvest machinery, small-scale production can use manual harvesting. Area must have high water table or irrigation. Requires no inputs other than water.
Removal	No information provided	Proven reversibility in Germany.	Proven reversibility, but volunteers (limited regrow from drop seeds) possible in the following season.	No information provided
Future climates	No information provided	No information provided	Grown widely in Europe, will adapt to local conditions if successive generations of seed are saved.	No information provided
Possible end uses	Combustion, ethanol, timber. The international market for the timber could compete with lower value bulk biomass sectors.	Primary end use is AD, as well as animal fodder. AD up to 100% feed-in rate and methane yield in AD 290 l/kg DM. If used at 100% feed-in rate in AD systems, the resulting high fibre digestate can be used to make paper.	Combustion, AD, ethanol, biodiesel, construction material, fibres, oil. Greatest value is in the utilisation of the fibre/seed, with energy as a co-product.	Value as biomass feedstock unclear. Although has been used as a fuel it is unlikely to be profitable as a bulk energy crop may have value as a biomaterial. A potential end market is the production of peat free compost. With 50 million tonnes of compost expected to be required per annum.
Feedstock quality	No information provided.	High in both sugar and fibre with higher protein content than maize. Well suited for AD.	Higher concentration of digestible cellulose and hemicellulose than other energy crops such as willow, and energy grasses. Blast fibre: 73-77% cellulose, 7-9% hemicelluloses, 2-6% lignin, Hurd: 48%, 21-25%, 17-19% respectively.	No information provided.
Environmental considerations	Carbon dynamics are unknown. Risks around importing foreign diseases. Biodiversity impacts requires research. Species have the potential to be invasive if allowed to seed. Seeding could be avoid through sterile hybrids. The need for irrigation during establishment could pose a risk in areas with limited water resources.	Soil carbon: Increases in below ground carbon of 5-8 t CO2 /ha/year reported. In Germany, payments for carbon credits are available to growers. No known pests in the UK thus insecticides are not needed. Long flowering period provides potential benefits for pollinators, but data is anecdotal. Water quality, nitrogen leaching, biodiversity and opportunities for phytoremediation: benefits expected especially in comparison to the alternative crop of maize, but data is anecdotal. Potential for invasiveness, but anecdotal evidence suggests low risk. Seeds have low germination rates, and roots are intolerant of transplantation	Susceptibility to wildfires needs to be considered. Reduced chemical usage: Does not require herbicide or pesticide during growth, can also reduce weeds and nematode pests' growth in the following crop. Can remove heavy metals from polluted soil. Wind pollinated but can provide a pollen source for pollinators. Anecdotal evidence for soil carbon sequestration: In addition to the conversion of the harvested biomass into long lived materials, roots and leaves are expected to add between 1.68 – 2.45 CO2/ha/yr to soils (based on the yield of 5.5 – 8 t ha) (calculated based on values from18) but long-term stability of this material is unknown.	Potential benefits for biodiversity, soil carbon, soil health, water quality and phytoremediation.
Co-benefits/payments	Leaves can be harvested for browsing.	Carbon trading, paper production and potential honey production. Co-production of fodder and biomass possible with multiple cuts per year.	Production of multiple products from a single crop. USA (Kentucky) and S. Australia reported a yield uplift of 10-20% in winter wheat after hemp.	Sphagnum farming may provide a mechanism to allow peat restoration whilst still providing income to landowners.
References or other sources of information	(6) Environmental Statement, Carbon Plantations Ltd. J S Young. Additional information: WeGrow Pheonix One, BIO TREE company	Additional information: Carbocert in Germany is facilitating the trading of Carbon credits. Workshop presentation slides from Tim Wood.	(7) Hemp Review: Industrial Hemp Cultivation in the UK, (2023). Additional information: Biomass Connect, Hemp as a Biomass Crop, 2023. H. Blandinières, et al. Multi-environment assessment of a yellow hemp (Cannabis sativa L.) cultivar's eco-physiology and productivity under varying levels of nitrogen fertilisation, Industrial Crops and Products 195 (2023). Workshop presentation slides from Alan Gay.	(8) Beadamoss (9) Fens for the Future (10) Strathclyde University – growing sphagnum to replace peat. Additional information: G. Gaudig, Sphagnum farming from species selection to the production of growing media: a review, Mires and Peat 20 (2018) 1-30.