Sustainable Bioenergy Feedstocks Feasibility Study

Final Report

Report for Department for Business, Energy and Industrial Strategy

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Appendices

Acknowledgements

BEIS has contracted Ricardo Energy & Environment in collaboration with its partners Beacon Tech Ltd, Centre for Ecology and Hydrology, Forest Research, Phytoremedia AB, and Uniper to conduct a feasibility study to examine the role that innovations could have in reducing the costs of producing bioenergy feedstocks, reducing greenhouse gas (GHG) emissions from bioenergy feedstock supply, and improving the profitability of bioenergy feedstock production for land managers. The results will inform a potential future innovation competition in this field.

The authors would like to acknowledge the contributions of Geraint Evans (BeaconTech Ltd), Jeanette Whittaker and Rebecca Rowe (Centre for Ecology and Hydrology), Steve Croxton and Susan Weatherstone (Uniper), Helen McKay and Geoff Hogan (Forest Research), and Par Aronsson and Ioannis Dimitriou (Phytoremedia), as co-authors of the supporting document "Sustainable Bioenergy Feedstocks Feasibility Study: Task 1 report" on which much of Sections 2 and 3 of this report are based, and also for their contributions to the assessment described in Section 5.

We would also like to acknowledge the knowledge and views provided by stakeholders from the energy crops and forestry sector at workshops held during the course of the project. We are also grateful for the expert input and review from the stakeholder advisory group which was convened for the last stage of the project, developing options for the design of a potential innovation competition.

Executive Summary

A range of evidence suggests that bioenergy will play an important role in a low carbon energy system as the UK transitions to net-zero (CCC, 2018 and CCC, 2019), but a significant supply of sustainable domestic bioenergy feedstocks at the scale required to meet these aspirations does not currently exist. In order to help address this challenge, technical innovations can help overcome the some of the barriers to increased supply and improve the rationale for landowners to produce feedstocks.

BEIS contracted Ricardo Energy & Environment to conduct a feasibility study to examine the role that innovations could have in reducing the costs of producing bioenergy feedstocks, reducing greenhouse gas (GHG) emissions from bioenergy feedstock supply, and improving the profitability of bioenergy feedstock production for land managers. This study forms an important component of the evidence base that will, along with other considerations and lines of evidence, assist BEIS in designing a possible innovation competition that helps increase the supply of sustainable UK bioenergy feedstocks.

The study began with a wide ranging literature review, and consultation with key stake holders to gather evidence on a range of aspects: the production process; greenhouse gas emissions; costs associated with production; environmental impacts and benefits from feedstock production; and barriers and challenges to profitable and sustainable production and uptake by landowners. The scope of the study was limited to steps in the production process occurring before the feedstock leaves the farm or forests. Breeding, planting, cultivation and harvesting were therefore all considered, as was any storage and pre-processing that could occur on the farm or in the forest.

Bioenergy feedstocks considered were perennial energy crops, Short Rotation Coppice (SRC) and Miscanthus, and in the forestry sector Long Rotation Forestry (LRF) and Short Rotation Forestry (SRF). For each feedstock, a wide range of potential areas where innovations could improve profitability and encourage the expansion of the supply chain were identified. A comprehensive account of the information gathered in this stage of the study is given in the accompanying supporting report, “Sustainable Bioenergy Feedstocks Feasibility Study, Task 1 Report” (Ricardo, 2020).

Each of the innovations was then assessed to identify those which would fit the remit of a potential innovation competition. For innovations that met the broad eligibility requirements, that the innovation was of a technological or biological nature and was at a suitable technology readiness level (TRL), a multi-criteria assessment (MCA) was carried out, which included consultation with stakeholders. Each innovation was assessed against relevant criteria related to the aims and objectives of the study. This allowed options which offered most potential to increase supply to be identified. Finally, the study developed options for the design of a potential innovation competition.

A scenario based approach was taken to examine the potential programme design. Key steps in the process were:

1. Establish fixed programme-level objectives.
2. Establish how parameters such as budget, timescale for implementation, timescale for impact realisation, type of programme and number of competitions might vary, and construct a number of scenarios that combined these in a range of ways.
3. Produce a ranked list of over 50 innovations from the MCA based on the fixed programme-level objectives.
4. Review the ranked list of innovations against each of the scenarios, noting pros and cons of different options, the impacts on the ranked list, and the impacts on the achievement of the programme-level objectives.

The five fixed programme-level objectives (which were agreed with BEIS) are:

1. **To increase the amount of sustainable biomass feedstocks produced in the UK.**
2. **To reduce the GHG emissions associated with biomass production up to the farm gate or forestry road.**

3. **To reduce the cost of biomass production up to the farm gate or forestry road.**
4. **To improve the resilience of UK biomass production to future climate change impacts.**
5. **To fund projects that accelerate the commercialisation of innovative technologies and processes.**

The key factor which will influence the competition design, the number of projects it might fund and its likely impact is the overall funding budget. As this is currently unknown, analysis was carried out and recommendations on competition design made for three budget levels (low, medium and high). For each of these budget levels, the likelihood of a competition meeting the programme level objectives was assessed for a number of scenarios in which other parameters were varied. These were:

- **Sector**; programme focussed on **energy crops** or **forestry** or both (i.e. **neutral**)
- **Timescale**: timescale over which impacts of increased supply should be seen – **short (**by 2030), medium (by 2045) long (by 2065)
- **Programme type**: targeted i.e. funded projects are on individual sites or multi-site, where innovations are tested on a number of sites

The results are discussed below, with ability to meet objectives and likelihood of risks colour coded as shown below.

Objectives rating	Risks rating
Highly likely	Unlikely
More likely	Less likely
Likely	Likely
Less likely	More likely
Unlikely	Highly likely

Low Budget Level

Table E1 summarises the results of the design analysis for a low budget level competition (£10 million). This leads to the key recommendation that at this budget level, the programme objectives of increasing sustainable supply would be best met by a competition that funds a single sector (energy crops), and includes projects that would have an impact in the short and medium term (i.e. to 2045) (Scenario B1).

Table E1: Results of competition design analysis for a low budget level

Scenario	A1	A2	B1	B2	C	D
Budget	L	L	L	L	L	L
Sector	Energy crops	Forestry	Energy crops	Forestry	Neutral	Neutral
Timescale	Short	Short	Medium	Medium	Short	Medium
Programme type	Targeted	Targeted	Targeted	Targeted	Targeted	Targeted
Ability to meet objectives						
Increase amount of UK production						
Reduce GHG emissions						
Reduce cost of production						
Improve resilience to future climate change impacts						
Acceleration of innovative technologies						
Likelihood of key risks occurring						
Failure to recruit sufficient applications						
Technology supply chain bottlenecks						
Sites are not sufficient to demonstrate impact						

Medium Budget Level

The key recommendation for a medium budget level (£20 million) is to run a competition that splits funding into two streams with a suggested £15m for energy crops and £5m for forestry. This is Scenario G in Table E2, and was selected due to the overall level of likelihood in achieving the competition objectives, balanced with the likelihood of key risks occurring.

Table E2: Results of competition design analysis for a medium budget level

Scenario	E	F	G	H
Budget	M	M	M	M
Sector	Neutral	Neutral	Neutral	Neutral
Timescale	Short	Short	Medium	Medium
Programme type	Targeted	Multi-site	Targeted	Multi-site
Ability to meet objectives				
Increase amount of UK production				
Reduce GHG emissions				
Reduce cost of production				
Improve resilience to future climate change impacts				
Acceleration of innovative technologies				
Likelihood of key risks occurring				
Failure to recruit sufficient applications				
Technology supply chain bottlenecks				
Sites are not sufficient to demonstrate impact				

High Budget Scenario

The analysis summarised in Table E3 shows that with a high budget level (£30 million) all of the competition design scenarios considered would have a high likelihood of increasing the amount of sustainable biomass produced in the UK.

Table E3 Results of competition design analysis for a high budget level

Scenario	I	J	K	L	M	N
Budget	H	H	H	H	H	H
Sector	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
Timescale	Short	Short	Medium	Medium	Long	Long
Programme type	Targeted	Multi-site	Targeted	Multi-site	Targeted	Multi-site
Ability to meet objectives						
Increase amount of UK production						
Reduce GHG emissions						
Reduce cost of production						
Improve resilience to future climate change impacts						
Acceleration of innovative technologies						
Likelihood of key risks occurring						
Failure to recruit sufficient applications						
Technology supply chain bottlenecks						
Sites are not sufficient to demonstrate impact						

The main recommendation, if a high budget level is available, is to run a competition that splits funding into two streams (with a suggested £20 million for energy crops and £10 million for forestry, (scenario N), including a multi-site demonstration workstream for specific energy crop innovations, and projects that would have an impact over timeframes ranging from the short (to 2030) to long (2065) term.

Overall, the work completed under the study allows for a conclusion that a future competition to support innovation in the area of biomass production would be feasible, have sufficient interest from the industry, and sufficient innovation potential to significantly increase sustainable biomass production in the UK.

1 Introduction

1.1 Background to study

A range of evidence suggests that bioenergy will play an important role in a low carbon UK energy system, as we transition to net zero (Committee on Climate Change, 2018), (Committee on Climate Change, 2019). For this to be the case, there will need to be a significant supply of sustainable domestic feedstocks. As yet, no such supply exists at scale. In order to help address this challenge, technical innovations may help overcome barriers to increased supply and improve the rationale for landowners to produce feedstocks. However, there are a considerable range of possible such innovations and if BEIS chooses to provide future innovation funding in this area, it will be important to have a robust evidence base to enable prioritisation. BEIS therefore commissioned this feasibility study from Ricardo to:

- Examine the role that innovations could have in reducing the costs of producing bioenergy feedstocks, reducing greenhouse gas (GHG) emissions from bioenergy feedstock supply, and improving the profitability of bioenergy feedstock production for land managers.
- Use this information to develop high-level, good value-for-money proposals for innovation competitions in bioenergy feedstocks.

This study forms an important component of the evidence base and, along with other considerations and lines of evidence, will assist BEIS in designing a possible innovation competition that helps increase the supply of sustainable UK bioenergy feedstocks.

1.2 Scope of the study

It was agreed with BEIS that the study would focus on non-food crop, plant based feedstocks, so would cover the production of perennial energy crops, conventional forestry, short rotation forestry, crop residues and novel annual crops in the UK. Traditional food and fodder crops (which might be used in biofuels production or anaerobic digestion) and waste feedstocks (such as animal manures and food waste) were excluded from the scope.

The scope of the study was also limited to steps in the production process occurring before the feedstock leaves the farm or forests. Breeding, planting, cultivation and harvesting are all therefore considered, as is any storage and pre-processing that could occur on the farm or in the forest. However, transport of feedstocks beyond the farm gate or forest road, and any further pre-processing of the feedstocks before conversion to energy or fuel have been excluded.

1.3 Study methodology

The study began with a wide ranging literature review, and consultation with key stakeholders to gather evidence on: the production process; greenhouse gas emissions; costs associated with production; environmental impacts and benefits from feedstock production; and barriers and challenges to profitable and sustainable production and uptake by landowners. It then identified a wide range of potential areas where innovations could improve profitability, reduce GHG emissions and encourage the expansion of the supply chain. In this stage of the project, Ricardo was assisted by its project partners, the Centre for Ecology and Hydrology, Uniper, BeaconTech Consulting and Phytoremedia. A comprehensive account of the information gathered in this stage of the study is given in the accompanying supporting report, "*Sustainable Bioenergy Feedstocks Feasibility Study, Task 1 Report*" (Ricardo, 2020). Key points to arise from the review are given in Section 2 of this report for perennial energy crops, Section 3 for foresty and Section 4 for annual crops and crop residues.

The next stage of the study took the wide range of innovations that had been identified and assessed which of these would fit the remit of a potential innovation competition. It is likely that any innovation competition would be part of the Energy Innovation Portfolio, and this requires that the technology readiness level of the innovation must be between 3 (applied research/proof of concept) and 8 (first of a kind) i.e. innovations which are still at a research or early pilot stage, or are already commercially available would not be eligible. Furthermore, it is necessary for the innovation to be of a technological or biological nature, or to have a substantial technological element.

For innovations that met both of these broad eligibility requirements, a multi-criteria assessment was carried out assessing each of the innovations against a number of relevant criteria related to the aims and objectives of the study. An initial assessment was made by the project team based on evidence gathered in the initial stage of the study through the literature review, stakeholder input and the project team's expert knowledge. This assessment was then reviewed, refined and adjusted at a workshop held in London in October 2019 and attended by a wide range of stakeholders, and a meeting held with Forestry Commission experts also in October 2019. This process is described more fully in Section 5 of the report.

The final stage of the study was to develop options for the design of a potential innovation competition. This was undertaken by Ricardo[1], with input from an independent advisory board with expertise in the bioenergy sector; an exploratory workshop with stakeholders was also held to gauge industry appetite and establish any particular barriers and challenges to participation in a potential programme. As several parameters concerning any potential programme are still unknown – in particular budget and detailed objectives for the programme - a scenario based approach was adopted for the analysis of programme options. This analysis and recommendations for programme design are discussed in Section 6 of the report and industry appetite for a competition in Section 7.

[1] All partners (apart from BeaconTech consulting) were excluded from this stage of the study to avoid possible future conflicts of interest.

2 Perennial energy crops

2.1 Introduction

The two energy crops most typically grown to date in the UK are Short Rotation Coppice willow (SRCw) and *Miscanthus* and so these are the focus of the following review. This section outlines the process steps in the production of SRC and *Miscanthus*, and gives an overview of the costs and greenhouse gas (GHG) emissions associated with each step. This is followed by discussion of a wide range of potential areas for innovation identified both through literature review, the expert knowledge of the project team and consultation with key stakeholders.

2.2 Production of energy crops

2.2.1 Production of SRC

The Short Rotation Coppice system utilises fast growing tree species such as willow or poplar which are repeatedly cut back to ground level (coppiced); the coppicing promotes vigorous juvenile growth from multiple stems which are then harvested at regular intervals through the crops lifespan of 15 to 20 years. The discussion in this section focuses on SRC willow as the most common species currently used in the UK, but much of the discussion is also relevant for SRC poplar.

Several varieties of willow have been specifically bred for use as energy crops, and a typical plantation will include at least two varieties in field to reduce issues with pests and disease. The willow is planted as cuttings in the spring using specialist equipment at a density of around 10,000 – 15,000 cuttings per hectare. After the first year of growth it is cut down to a low stump (or stool) that readily develops multiple shoots, which are left to grow for two to three years before harvesting the first crop in winter. The crop is subsequently harvested every three to four years. While the equipment needed to harvest willow is not particularly specialist, many farmers will not own harvesting equipment and will rely on contractors. An example lifecycle for SRC crops from pre-establishment to first harvest is given in Figure 2-1. On a three-year SRC cycle, years 1-3 will be repeated following each harvest, and typically an SRC plantation will have 6-10 cycles, before plant losses and falling yield (stem numbers) mean that it becomes less economical to harvest.

Figure 2-1: Production cycle for Short Rotation Coppice (3-year cycle)

<table>
<tr><th></th><th>Year -1</th><th>Year 0</th><th>Year 1</th><th>Year 2</th><th>Every 3 years</th></tr>
<tr><td>Jan</td><td rowspan="7">Existing crop</td><td rowspan="3">Site preparation</td><td rowspan="3">Dormancy/Cut back</td><td rowspan="3">Dormancy</td><td rowspan="3">Harvest</td></tr>
<tr><td>Feb</td></tr>
<tr><td>Mar</td></tr>
<tr><td>Apr</td><td rowspan="2">Planting</td><td rowspan="7">Growth</td><td rowspan="7">Growth</td><td rowspan="7">Growth</td></tr>
<tr><td>May</td></tr>
<tr><td>Jun</td><td>Gap filling</td></tr>
<tr><td>Jul</td><td rowspan="4">Growth</td></tr>
<tr><td>Aug</td><td rowspan="5">Site preparation</td></tr>
<tr><td>Sep</td></tr>
<tr><td>Oct</td></tr>
<tr><td>Nov</td><td rowspan="2">Senescence</td><td rowspan="2">Senescence</td><td rowspan="2">Senescence/ Harvest</td><td rowspan="2">Senescence</td></tr>
<tr><td>Dec</td></tr>
</table>

Source: derived from (Croxton, 2015)

Steps in the production of SRC in the UK, from planning and site preparation through to clearance of the site at the end of the plantation's life are described in Table 2-1. Every field can have different challenges and conditions, meaning a blanket style approach, in terms of preparation and steps to achieve a successful plantation, is not good practice. Not all steps in Table 2-1 will be needed for every site, and each step should be reviewed for applicability for each situation and area being planted.

Table 2-1: **Key process steps in SRC Production**

Step	Sub-steps	Description
Initial planning	Site assessment	A soil analysis and area assessment of the proposed planting area is required to identify the requirements for preparing the area for planting.
Site preparation	Sub-soiling	Some sites may require compacted layers of soil to be broken up in advance of ploughing.
	Drainage	While almost all soils are suitable for SRC, heavy clay soils may need drainage installation to reduce water logging, but this is very rare.
	Weed removal	Any existing weed burden should be removed before ploughing and planting – usually this is performed through the use of a total herbicide, such as glyphosate. Several applications may be required prior to planting if weed burden is high.
	Ploughing	Soil needs to be ploughed to a minimum of 30 cm, ideally >30 cm, and depending on soil types will benefit from over-winter weathering.
Planting	Harrowing and levelling	The required depth of the cultivator/power-harrow operation will depend on what is being planted (rods or cuttings). Conventional rod and cutting planters require a minimum of 15 cm depth of fine level soil.
	Planting	When using rods, the rod is inserted into the ground and cut to approximately 20 cm in length with approximately 2 cm sticking out of the ground. Cuttings are inserted intact (not cut) and left with about 2 cm sticking out of the ground
	Herbicide	Soil acting herbicides are generally applied within three days of planting to suppress weed growth until the shoots are established
	Fencing	Can be required to protect new shoots from rabbits or dear in year 0 at some sites
Initial growth	Gap filling	Particularly when using rods, replacement of cuttings that fail to establish may be needed, or if the cutting has died due to drought, damage, or pest attack, or gaps occurred at time of planting.
	Pesticides	Weed control, particularly of grass, will be required in the first year of establishment, and potentially in the following year after cutting back if SRC growth is slow to get away. It is also common to use a total herbicide at the end of the first year following senescence, after cut back and while the SRC is dormant. Some varieties can be susceptible to foliar disease (rusts) and insect pest attacks (willow beetle); in certain situations these may require application of pesticides to assist with control.
	Fertilisation	NPK fertiliser is likely to be required prior to planting and after each harvest, but soil analysis will always be used to determine what fertiliser (if any) should be applied. In poorer quality soils, nutrient deficiency can be an issue, with iron, magnesium, copper and boron all required by the growing plant to be assessed and monitored.
	Mechanical weeding	As well as herbicide application, physical removal of weeds between rows may be required in early establishment years
Harvest	Harvest & chipping	Forage harvesters with specific cutting systems are generally used to cut and chip, or billet (cut into length approximately 10-20 cm long) the crop in a single step early in the year whilst the plant is dormant.
Storage	Drying	Storage of chips/billets is usually outside on concrete pads, or part of a field that is easily accessible for loading a collection vehicle. If required, drying undercover can be undertaken, either using natural or mechanical ventilation systems.

Step	Sub-steps	Description
Reversion	Stump removal/ grinding	SRC plantations are generally viable for 15-25+ years. Once yield or viability of the plantation starts to drop, a decision is made to revert the field and start afresh with a new planting, or change the field use

Source: derived from (Croxton, 2015)

2.2.2 Production of *Miscanthus*

Miscanthus is a perennial energy crop that can grow to heights of 2.5 to 3.5 m in one growing year once it is well established. *Miscanthus* is usually grown from rhizomes, which are planted in spring at a density of around 25,000 per hectare to achieve a targeted establishment rate of 10,000 to 15,000 per hectare. New shoots emerge around March each year, growing rapidly in June to August, producing bamboo-like canes. The *Miscanthus* dies back in the autumn/winter, when the leaves fall off, and the dry canes are harvested in winter or early spring. After its first full year of growth it can be harvested annually for biomass for 20 years or more. shows an example timeline for the *Miscanthus* growth cycle.

Figure 2-2: Production cycle for *Miscanthus*

	Year -1	Year 0	Year 1	Year 2	Year 3 +
Jan				Dormancy	Dormancy
Feb		Site preparation	Dormancy		
Mar				Harvest	Harvest
Apr	Existing crop	Planting	Topping/Mowing		
May			Gap filling		
Jun		Gap filling			
Jul				Growth	Growth
Aug		Growth	Growth		
Sep					
Oct	Site preparation				
Nov		Senescence	Senescence	Senescence	Senescence
Dec					

Source: derived from (Croxton, 2014)

Miscanthus can be grown in all soil types, in both wet and dry conditions, although establishment can be difficult on 'marine clay' type soils, and its yield will vary depending on soil type, and water availability. Generally, it produces higher yields when there are higher levels of soil water or rainfall available. The basic steps in preparation, establishment and harvesting of a *Miscanthus* crop are shown in Table 2-2. Depending on factors such as the soil type, climate, and the previous land use, not all of these steps may be required, and at some points there are alternative options.

2.3 Greenhouse gas emissions from energy crops

GHG emissions from the stages of production which occur up to the farm gate for SRC willow and *Miscanthus* are shown in Figure 2-3. They represent 'typical' cultivation and harvesting conditions and emissions at any particular site could vary from these. They exclude changes in emissions from soil carbon (which are discussed further below), but include emissions from all operations in cultivation from planting to harvesting and the emissions associated with 'capital goods' (fencing and machinery) as well as agrochemicals, emissions from these farm based production steps are estimated to be 3.65 kg CO_2e/MWh of biomass feedstock for SRC and 3.5 kg CO_2e/MWh for Miscanthus. A further breakdown of emissions by source is shown in Figure 2-4 for SRC and in Figure 2-5 for *Miscanthus*.

Table 2-2: Process steps in *Miscanthus* cultivation

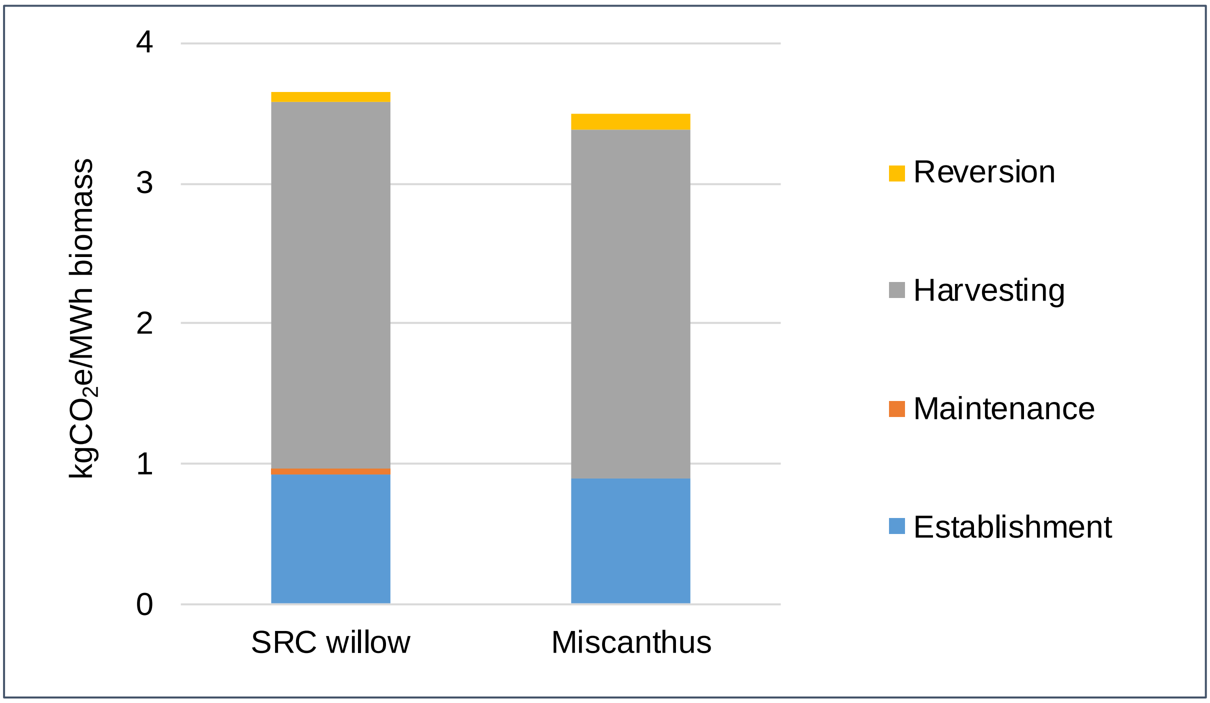
Step	Sub-steps	Description
Initial planning	Site assessment	A soil analysis and assessment of the proposed planting area is required to identify the preparation requirements of the proposed planting area.
Site preparation	Sub-soiling	Some sites will require compacted soil to be broken up in advance of ploughing
	Weed removal	Any existing weed burden should be removed before ploughing and planting – usually this is performed using a total herbicide, such as glyphosate. Several applications may be required prior to planting if weed burden is high
	Ploughing	Soil needs to be ploughed to a minimum of 30 cm, and depending on soil type, may benefit from over winter weathering.
Planting	Harrowing and levelling	The power-harrow operation is required to be down to a minimum of 15 cm, as planting will occur at 10–12 cm. Planters require a 15 cm depth of fine level soil to adequately cover planted rhizomes.
	Planting	Usually from rhizome pieces, though nursery grown plantlets from cuttings or (in development) seed are also becoming available, and direct seed sowing is being tested.
	Compression	Following rhizome planting, the soil needs to be rolled/compressed with a ring roller to remove air from around the rhizome, to trap and conserve moisture avoiding the risk of desiccation to the rhizome, and to reduce the chances of soil pests being able to attack the rhizome.
	Herbicide	A pre-emergent herbicide is typically applied to reduce weed competition within three days of planting, to provide the best control of competing weeds. Further applications of herbicide will likely be required in the growing crop for broadleaf weeds during year 0 and year 1. Grass weeds are only controlled over the winter months, usually using glyphosate, whilst the *Miscanthus* crop is dormant.
	Film	Establishment of seed and plantlets can be improved by the use of a biodegradable plastic film, similar to that used when planting early maize crops to avoid damage from frost and retain moisture.
	Rabbit fencing	Can be required to protect tender new shoots in spring, and usually only required on a temporary basis until crop is strong enough to outgrow grazing pests. Strong smelling organic products (typically garlic based) are also sometimes used and sprayed on the crop to act as a deterrent to rabbits and deer.
Initial growth	Gap filling	When using rhizome or plantlets, it is sometimes necessary after emergence to manually plant additional material to in fill gaps, where rhizomes or plantlets have died.
	Pesticide	Additional post-emergent weed control is generally required during establishment years 1 to 2. Incidence of disease damage is usually low and not treated. There are no pesticides available to control soil pest risks in *Miscanthus*.
	Irrigation	Usually not required but may be needed after planting, particularly if it was delayed to late spring and during dry warmer temperatures.
	Fertilisation	Nutrient input requirements are generally considered to be low, so that nitrogen applications are not typically needed. However, soil analysis may indicate that additional fertilisation is needed, e.g. if the soil has very low available nitrogen.

Step	Sub-steps	Description
	Topping/ mowing	After first year of growth the field needs to be cut back, with the material left in the field. Depending on the growth rate, topping may need to be repeated in year 2 (instead of a harvest).
Harvest	Cutting	Usually done in early spring, when cane moisture content is lower and before new growth starts (Feb – April).
	Swath	If material is to be baled, it must be left swathed in order to further dry and enable improved pick-up and ensure continuous baler operation. Leaving in the swath has seen moisture content reduce to below 14% in dry springs.
	Baling	May be part of single line process or delayed to allow further drying or natural leaching/washing of the swath by rainfall.
	Harvest and chipping	As an alternative to baling, cut/chipped material may be chipped directly into a tractor/trailer. This is usually only performed if being used locally as the bulk density is 90-100kg/m^3.
Storage	Drying	If required, further drying can be undertaken during storage, either using natural ventilation (chip) or mechanical ventilation (bales)
	Storage	Baled material is usually stored in stacks, chipped material in heaps, with or without shelter. If stored uncovered there may be some losses through rain damage, but these are usually restricted to the outer layers.
Reversion	Reversion	At the end of the productive cycle, herbicide is used to kill the shoots and the rhizome then dies, requiring ploughing and cultivating to return the field for re-planting or to another crop.

Source: derived from (Christian & Haase, 2001; El Bassam & Huisman, 2001; Croxton, 2014)

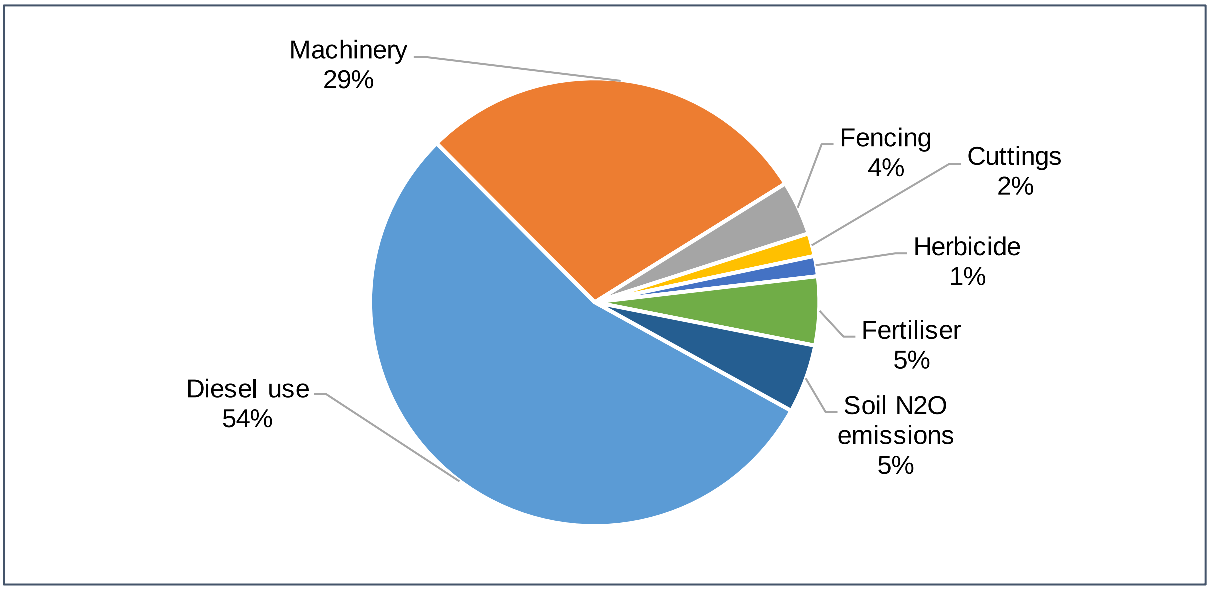
For both crops, emissions arise principally in the harvesting step, and within that mainly from diesel use. In the case of SRC, emissions associated with production and maintenance of the harvester are also significant. The latter reflects the relatively small number of operational hours that such specialist equipment typically has over its lifetime, meaning that production related emissions are relatively high per hour of operation compared to, for example, transport vehicles. Emissions from the production of agricultural machinery are not as significant for *Miscanthus*, as this is harvested every year so utilisation factors for the machinery are higher. Diesel use contributes the highest share to overall emissions in the establishment phase, but in the case of SRC, where some application of nitrogenous fertiliser is assumed, emissions from production of nitrogenous fertiliser and the soil N_2O emissions arising from is application also contribute significantly.

Figure 2-3: GHG emissions associated with on-farm production of SRC and miscanthus



Source: derived from (North Energy, Forest Research and NNFCC, 2018)[2]. Includes emissions up to farm gate only; emissions from transport and processing post farm gate are excluded

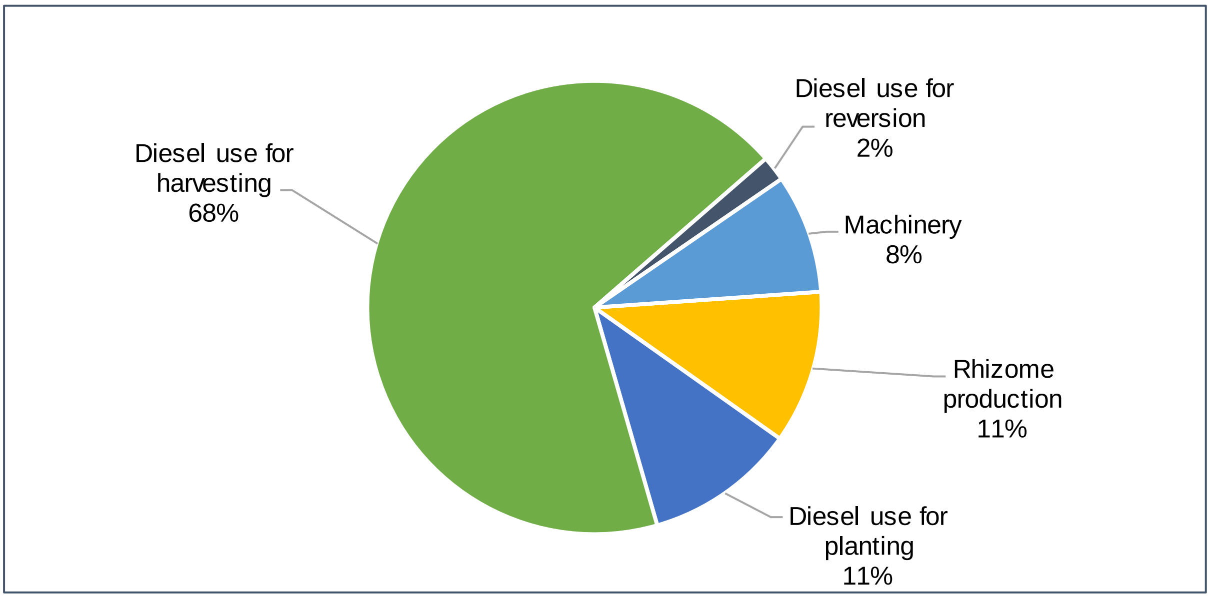
Figure 2-4: Sources of GHG emissions associated with production of SRC willow on farm



Source: derived from (North Energy, Forest Research and NNFCC, 2018); Includes emissions up to farm gate only; emissions from transport and processing post farm gate are excluded

[2] Note the applications of fertiliser for *Miscanthus* production has been adjusted from the original data set (North Energy, Forest Research and NNFCC, 2018) to reflect evidence from stakeholders that current best practice is to have no application of fertiliser.

Figure 2-5: Sources of GHG emissions associated with production of *Miscanthus* on farm



Source: derived from (North Energy, Forest Research and NNFCC, 2018)[3]. Includes emissions up to farm gate only; emissions from transport and processing post farm gate are excluded

An additional consideration when looking at the GHG fluxes associated with perennial energy crops is their impact on soil carbon. The ELUM project funded by the ETI (Energy Technologies Institute, 2015) measured changes to soil carbon at depths to one metre. It then developed a meta model using the ECOSSE soil carbon and GHG model produced by the University of Aberdeen, to assess the potential impact on soil carbon stocks and soil GHG emissions in the UK of changes in land use to growing bioenergy crops. These were assessed for transitions from arable land growing rotational crops (including land where rotational or temporary grassland is part of the rotation), permanent uncultivated grass land and forestry. The results for modelling of soil carbon changes over a 35 year period (Richards, et al., 2017) are shown as annualised changes in Table 2-3. There is a large variation in values, and empirical studies show that it is generally the soil carbon stock of the land prior to planting that is important in determining the magnitude and direction of change in soil carbon stock (Rowe, et al., 2016) (Whitaker, et al., 2018). Soils with high carbon stocks prior to planting of energy crops are at greatest risk of soil carbon loss, and soils with a low carbon stock prior to planting are more likely to see an increase in soil carbon.

Table 2-3 shows that planting of SRC on land previously used for rotational crops will generally lead to an increase in soil carbon, and that in these cases this will often offset the emissions associated with production, leading to an overall negative GHG flux. For soils where there is a net decrease in sol carbon, the increase in CO_2 emissions from loss of soil carbon (13 kg CO_2e/MWh of SRC feedstock) could be more than triple the emissions associated with production reported in Figure 2-3 of 3.7 kg CO_2e/MWh of SRC feedstock. However, even where this is the case, total emissions (i.e. including those caused by the land use change) from production of the feedstock at the farm gate would still be only about 17 kg CO_2e/MWh of SRC feedstock, meaning that use of the biomass for energy production would still deliver substantial GHG savings compared to fossil fuel alternatives. Results for *Miscanthus*, show a similar pattern, on average leading to an increase in soil carbon.

[3] Note the applications of fertiliser for *Miscanthus* production has been adjusted from the original data set (North Energy, Forest Research and NNFCC, 2018) to reflect evidence from stakeholders that current best practice is to have no application of fertiliser.

In the case of permanent grassland, the results from the modelling suggest that if permanent uncultivated grassland was converted to SRC or *Miscanthus*, there is likely to be a net decrease in soil carbon. However as previously, total emissions (based on the mean value for soil carbon emissions) would still be under 40 kg CO_2e/MWh meaning that energy produced from the biomass would still have substantially lower GHG emissions than fossil fuel-based alternatives. It should also be noted that about 17% of UK grasslands are temporary or rotational grasslands and changes in soil carbon due to conversion from these types of grassland would be within the range reported for rotational crops. As noted, above, it is likely to be the soil carbon stock prior to planting that is important in determining whether there is a soil carbon loss or gain.

It should be noted that the data in Table 2-3 were from sites which due to their age were not planted using current best practice techniques for establishment. It is therefore likely that there are further opportunities to reduce soil carbon impacts through improved establishment techniques.

Table 2-3: GHG flux from change in soil carbon due to direct land use change to SRC

Original land use	Annualised change in soil carbon when converting to SRC			Annualised change in soil carbon when converting to *Miscanthus*		
	Mean	Low	High	Mean	Low	High
	t CO_2e per ha per year			t CO_2e per ha per year		
Rotational crops	-0.53	-3.27	0.78	-1.58	-3.48	0.02
Permanent grassland	2.00	0.94	5.32	1.28	-0.05	4.22
	kg CO_2e/MWh biomass feedstock produced[a]			kg CO_2e/MWh biomass feedstock produced[a]		
Rotational crops	-8.9	-54.3	13.0	-29.7	-65.3	0.4
Permanent grassland	33.2	15.7	88.5	24.0	-0.9	79.3

[a] Changes per ha have been converted to a per MWh basis using the annualised yields specified in the assessment of GHG emissions from production of 11.4 oven dried tonne per ha (odt/ha) per year for SRC and 10.7 odt/ha per year for *Miscanthus*.

Source: derived from (Richards, et al., 2017)

2.4 Production costs

The costs of production reported in the academic literature, other published literature and from stakeholder consultation were reviewed and used to produce a set of representative baseline costs for each step in the production of SRCw and Miscanthus. These costs were then combined with yield data to produce estimates of the cost per tonne (and GJ) of SRCw and *Miscanthus* at the farm gate, on a levelized cost basis. The representative baseline costs were taken from sources where the provenance was known, strong and data was clearly presented in a transparent way; all the data used was peer reviewed by experts within the Project team.

Production costs will inevitably be variable as they are influenced by farming practices and yields, and different assumptions regarding, for example, agronomic practices will result in different farm-gate production costs. In order to give some idea of the potential variance in production costs which could be expected, a high and low case was also estimated; the impact of land rent on the price of the biomass produced was also considered. Full details of the cost literature review and how the baseline costs were established is given in the supporting document (Ricardo, 2020).

2.4.1 Costs of SRC production

The cost of production of Short Rotation Coppice (willow and poplar) arises from three phases: establishment, which comprises soil preparation, plant material acquisition, weed control and planting;

production, which comprises a yield building phase followed by a yield stabilisation phase; and reversion when the plant material is removed and the field made available for a new crop.

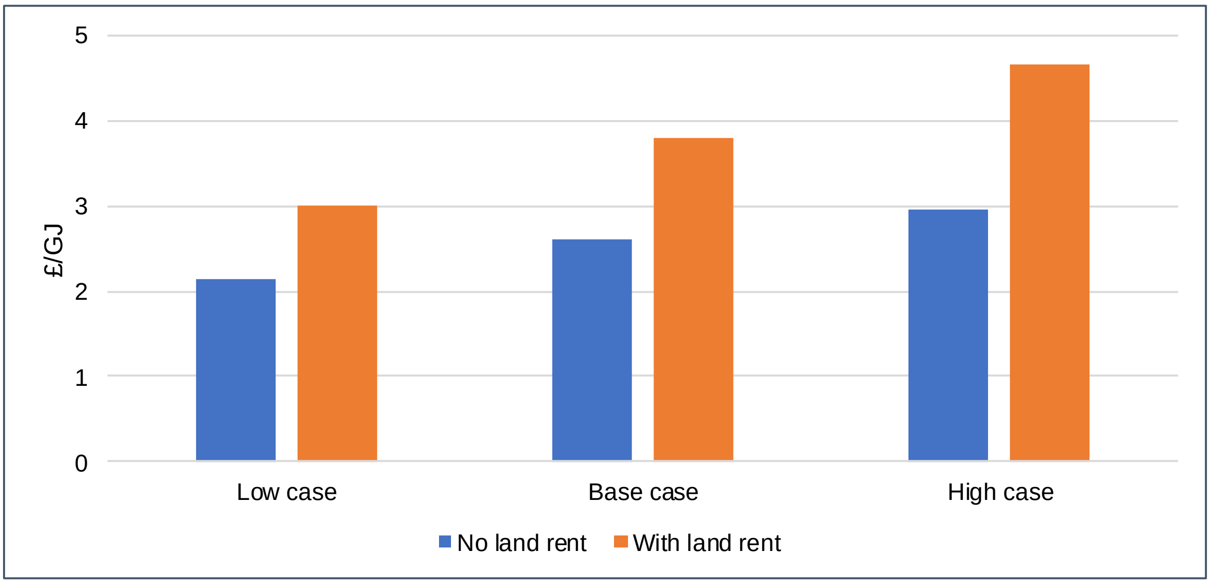
Details of estimated costs for each of these steps are given in Appendix 1, with a full description of their derivation in the supporting document. These costs were used in a discounted cash flow model to calculate the overall costs of production. The results are shown in Table 2-4 on both an undiscounted and discounted basis. For the discounted values (at 5% and 10%) the cost is a levelized cost of production and represents what the farmer would need to receive to achieve an internal rate of return equal to the discount rate. With a 5% discount rate, the cost of producing SRC is estimated to be £$_{2019}$ 50/odt (£$_{2019}$ 2.6/GJ), while at 10% it rises to £$_{2019}$ 60/odt (£$_{2019}$ 3.1/GJ).

These costs exclude land rent, because it is a variable which would not be affected by technical innovations. However, it is useful to understand the effect that is has on the price of the biomass produced, as this will affect the price that the farmer would need to receive for the biomass in order to make its production profitable. Defra data indicates an average land rent of £181/ha/year for England in 2016/17. This increases to a maximum of £260/ha/year for high value agricultural land in the East of England and falls to a minimum of £130/ha in the north west of England (DEFRA, 2018). Figure 2-6 shows that the impact of land rent on production costs can be significant. Payment of an average land rent increases the baseline production cost by about 45% to £3.8/GJ, while under the high case, with a maximum land rent value, costs are increased by 58%.

Table 2-4: Modelled cost of SRC at the farm gate (£$_{2019}$)

Parameter	Units	Case	Undiscounted	5% discount rate	10% discount rate
Total cost per hectare	2019£/ha	Low	7,171	4,618	3,386
		Base	8,749	5,635	4,130
		High	9,723	6,366	4,748
Total discounted production over lifetime	odt/ha	All cases	205	114	69
Production costs	2019£/odt	Low	35.0	40.6	48.8
		Base	42.7	49.6	59.5
		High	47.4	56.0	68.4
Production costs	2019£/GJ	Low	1.8	2.1	2.6
		Base	2.2	2.6	3.1
		High	2.5	2.9	3.6

Figure 2-6: Impact of land rent on SRC production costs (at 5% discount rate)



An understanding of the contribution of process steps to overall production costs is useful for understanding where innovation might best help reduce overall costs. The most significant component of production costs (excluding land rent) is the harvesting phase, followed by planting which is dominated by the cost of planting material (Figure 2-7). When examined from the perspective of costs per tonne (or GJ) of biomass produced, costs are most sensitive to the yield achieved (Figure 2-8) with harvesting costs and to a lesser extent planting costs also having a significant effect.

Figure 2-7: Contribution of process steps to SRC production costs

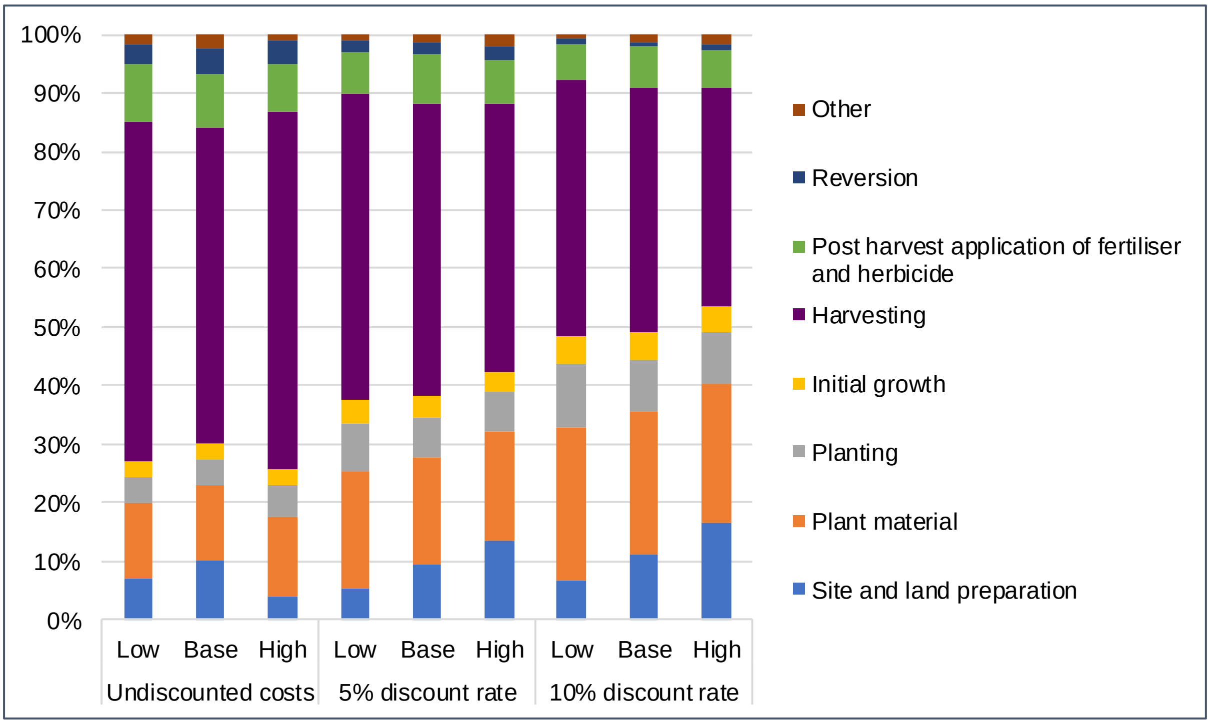
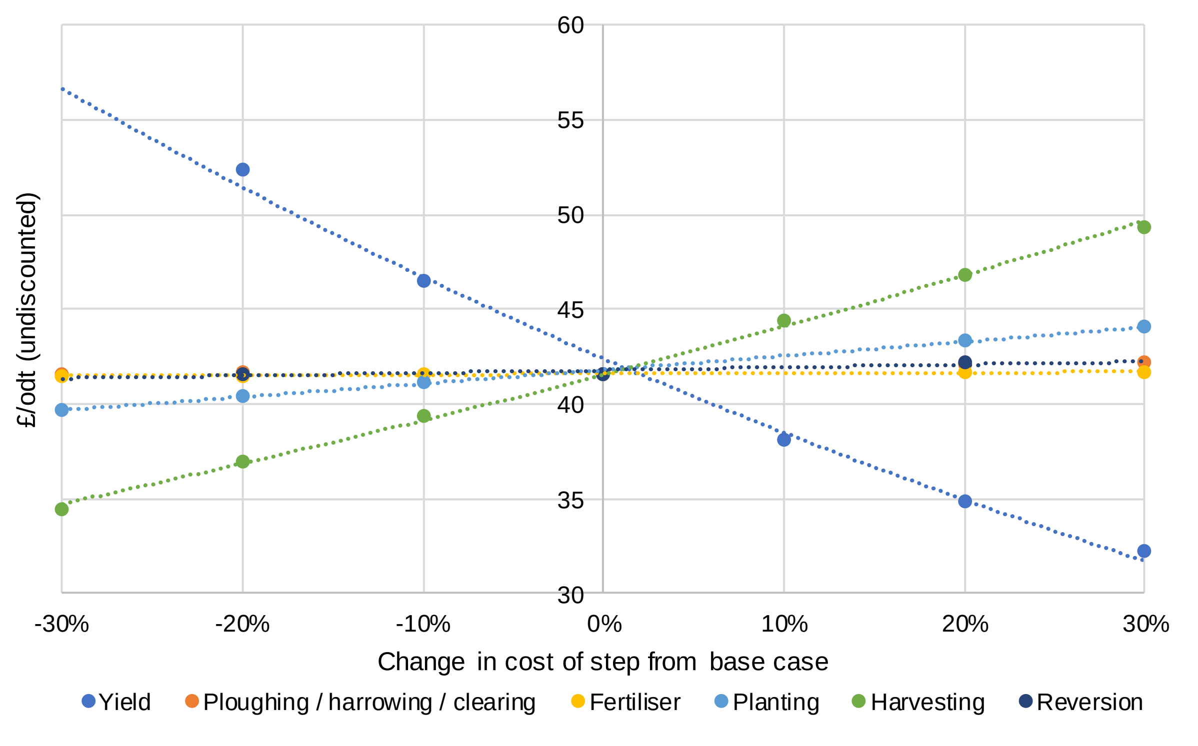


Figure 2-8: Sensitivity analysis of SRC production costs



2.4.2 Cost of *Miscanthus* production

As for SRC, the cost of production of *Miscanthus* arises from three phases: establishment, which comprises soil preparation, plant material acquisition, weed control and planting; production, which comprises a yield building phase followed by a yield stabilisation phase; and reversion when the plant material is removed and the field made available for a new crop.

As for SRC, details of estimated costs for each of these steps are given in Appendix 1, with a full description of their derivation in the supporting document. Total production costs based on using these costs in a discounted cash flow model are shown in Table 2-5. As for SRC, for the discounted values (at 5% and 10%) are the levelized cost of production and represent what the farmer would need to receive to achieve an internal rate of return equal to the discount rate. With a 5% discount rate, the cost of producing *Miscanthus* is estimated to be $£_{2019}$ 46/odt ($£_{2019}$ 2.6/GJ), while at 10% it rises to $£_{2019}$ 59/odt ($£_{2019}$ 3.3/GJ). As with SRC, the impact of land rent on production costs is significant (Figure 2-9). Payment of an average land rent increases the baseline production cost (at a 5% discount rate) by about 47% ($£_{2019}$1.2/GJ) to $£_{2019}$3.8/GJ, while under the high case, with a maximum land rent value, costs are increased by similar proportion rising $£_{2019}$1.7/GJ to $£_{2019}$5.6/GJ.

The most significant component of production costs (excluding land rent) is the harvesting phase (Figure 2-10), within which baling of the cut miscanthus is the significant cost. Planting is also a significant cost. When examined from the perspective of costs per tonne (or GJ) of biomass produced, costs are, as for SRC, most sensitive to the yield achieved (Figure 2-11) with harvesting costs also having a significant effect.

Table 2-5: Modelled cost of *Miscanthus* at the farm gate (£$_{2019}$)

	Units	Case	Undiscounted figures	5% discount rate	10% discount rate
Total cost per hectare	2019£/ha	Low	6,710	4,334	3,168
		Base	8,303	5,492	4,105
		High	12,673	8,253	6,068
Total discounted production	odt/ha	All cases	219	118	70
Production costs	2019£/odt	Low	27.5	36.6	45.4
		Base	34.1	46.4	58.9
		High	52.0	69.8	87.0
Production costs	2019£/GJ	Low	1.5	2.0	2.5
		Base	1.9	2.6	3.3
		High	2.9	3.9	4.8

Figure 2-9: Impact of land rent on *Miscanthus* production costs (at 5% discount rate)

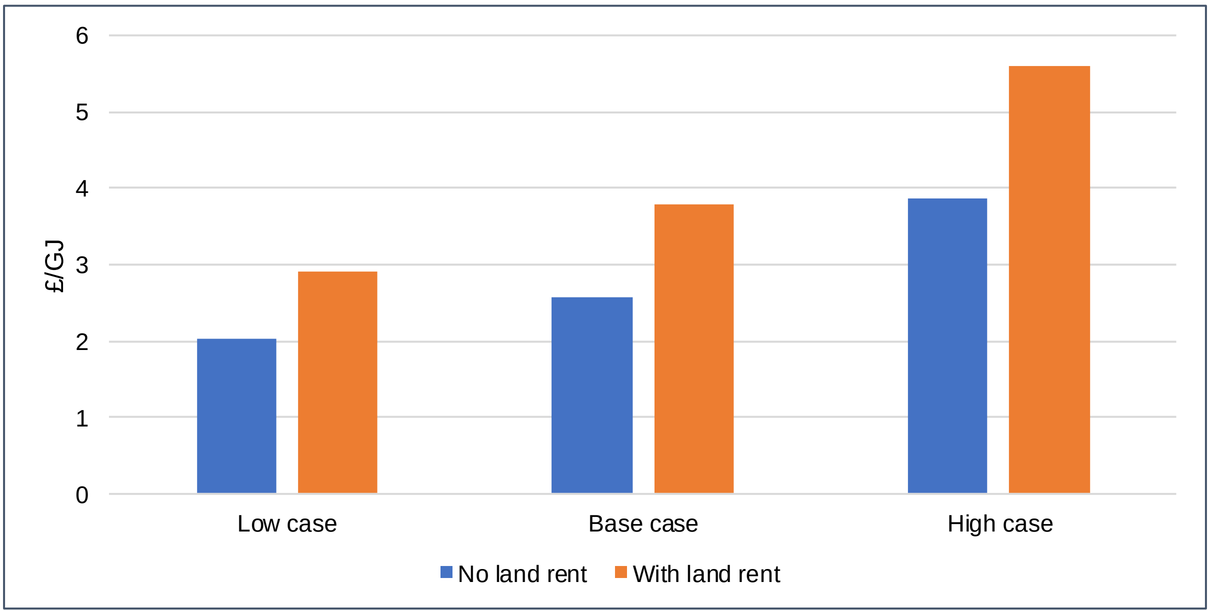


Figure 2-10: Contribution of process steps to levelized cost of *Miscanthus* production

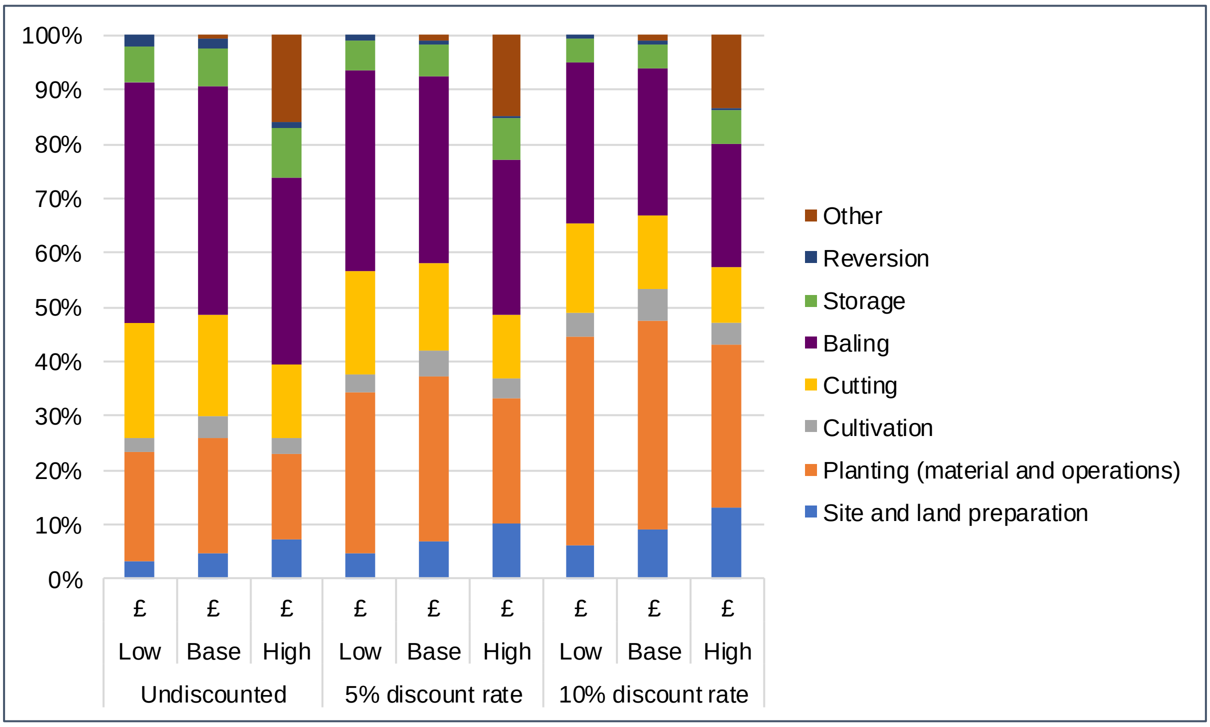
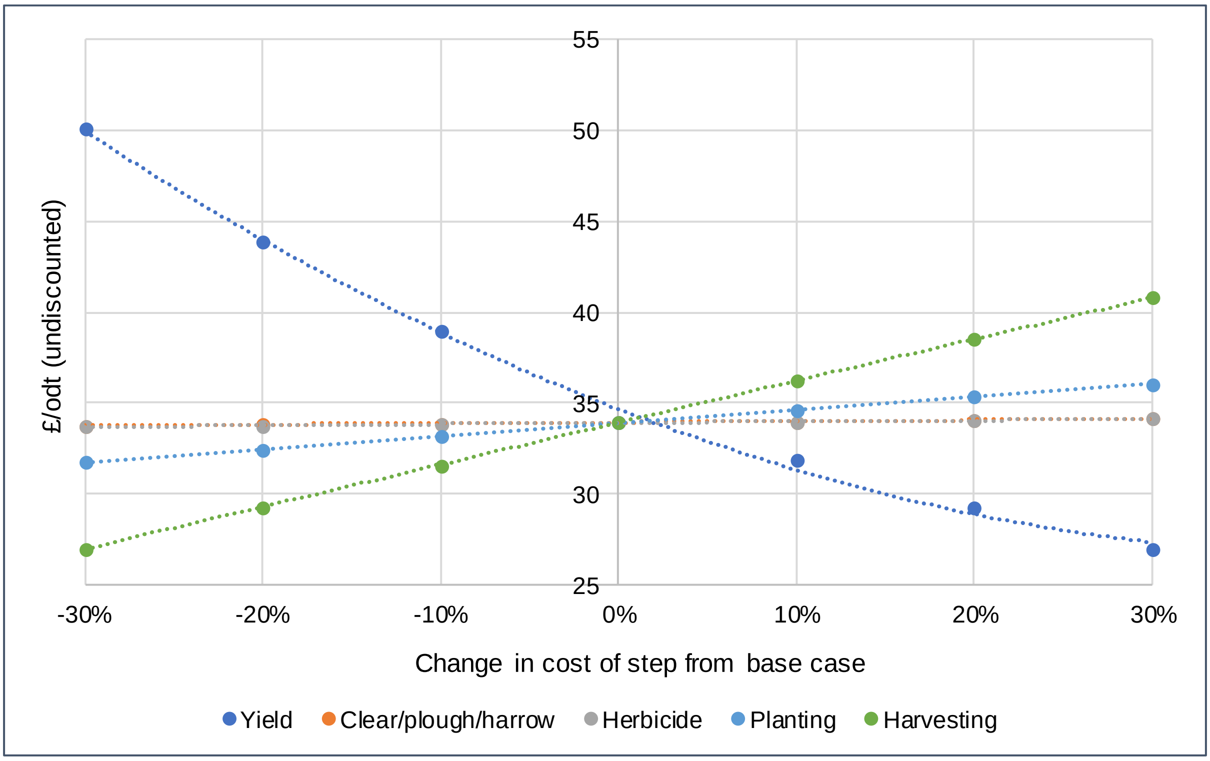


Figure 2-11: Sensitivity analysis of *Miscanthus* production costs



2.5 Innovation areas for perennial energy crops

This section describes innovations which could address challenges and barriers within the sector and accelerate the uptake of energy crops by landowners and land managers by improving yields and productivity, improving economic returns or providing wider environmental or societal benefits. They are grouped into the following categories:

- breeding and propagation of planting materials,
- agronomic innovations in planting and establishment,
- agronomic innovations in crop management,
- harvesting and processing innovations,
- agronomic innovation in alternative uses of energy crops,
- land use innovation to harness the environmental benefits of energy crops and
- innovations in information supply and engagement to address barriers to uptake.

Evidence from the literature review carried out for the study (as reported in (Ricardo, 2020) is summarised first and is followed by additional points made by stakeholders.

2.5.1 Breeding and propagation of planting materials

2.5.1.1 SRC

The most extensive germplasm repository for willow globally is in the UK at Rothamsted Research, which contains over 1,500 accessions (Trybush, et al., 2008). Breeding programmes in the UK and US have made significant progress. For SRCw, F1 hybrids have produced impressive yield gains over parental germplasm by capturing hybrid vigour, with over 30 willow clones commercially available in the US and Europe and a further circa 90 in pre-commercial testing (Clifton-Brown, et al., 2018). Crosses are still coming out with five varieties registered but there is considerable scope for further improvements to yield and resilience through breeding and screening programmes, however there are significant challenges in quantifying the diversity of traits in the field because of the size of individual willow plants and plantations. Opportunities for innovations include:

- In SRC poplar and willow, novel remote sensing field phenotyping is being deployed to assist breeders but needs further R&D (Clifton-Brown, et al., 2018)
- Genetic tools have potential to enable more efficient plant breeding of willow through the identification of candidate genes and genetic markers for traits (Clifton-Brown, et al., 2018; Hanley & Karp, 2013).
- Conventional breeding takes 13 years via four rounds of selection from crossing to selecting a variety, but this could be reduced to seven years if micropropagation and marker assisted selection were adopted (Hanley & Karp, 2013; Palomo-Ríos, et al., 2015).
- Microencapsulation of stem and bud sections for planting using the CEED^{TM} system has been applied successfully with *Miscanthus* but hasn't been developed for SRCw (Xue, et al., 2015). The advantage of this is that it would enable faster scaling up but there is significant development required to deliver a robust reliable establishment and may therefore be worth investigating.

Additional innovations proposed in stakeholder consultations include:

- Multi-site trials to test the performance of new varieties under a range of climate and edaphic conditions; these trials should extend beyond the UK to capture environmental extremes to which crops could be exposed under future climate scenarios.
- Flood tolerance (inundation tolerance and resilience to water flow) is a significant knowledge gap. There has been no breeding or screening of current varieties to maximise flood resilience and mitigation. This will need some novel biological research. Screening of existing

varieties could provide a quick win, but these are genetically quite narrow so screening the wider germplasm collection would have more impact.

- Screening and breeding of varieties for drought prone sites has begun, but tailoring varieties most suitable to lighter, more drought prone sites could be beneficial.
- Screening / breeding of varieties for contaminated land. Currently standard varieties are planted but there is great potential to develop clones for phytoextraction or phytostabilization. No work has been done in this area.
- Variety development/breeding for slower spring starting to improve establishment success or quicker autumn senescence to enable harvesting earlier in the year.
- Multiplication sites for generating SRCw planting stock currently have a low capacity. If large areas are to be planted, these sites need to be invested in urgently alongside innovation to increase the scale of planting stock generation. One suggestion is to work with plant breeders to set up a system whereby existing plantations can be used as nurseries to supply willow rods on a region by region basis rather than importing willow rods from Europe.
- Rabbit fencing is recommended best practice in the establishment year but often not installed due to cost. Some varieties are more resistant to rabbit damage than others, so this needs testing to inform growers.

2.5.1.2 Miscanthus

Innovation in this area is focused on a range of short- and medium-term objectives, and are aimed at improving establishment rates and biomass yield, decreasing costs of propagation and establishment, expanding the range of locations and site types on which *Miscanthus* can be grown and improving climate resilience. Three extensive reviews with industry and academic authorship summarise the current state-of-the-art in *Miscanthus* breeding and propagation scaling up and the recommendations and innovations proposed in these reviews are summarised below (Clifton-Brown, et al., 2018; Clifton-Brown, et al., 2017; Xue, et al., 2015).

Miscanthus breeding led by Aberystwyth University, UK, over 14 years has delivered a range of conventionally bred seed-based interspecies hybrids which are now in upscaling trials. However, there is still considerable scope for breeding to deliver improved hybrids with a range of desirable traits appropriate for particular land types or climatic regions, climate resilience (drought and frost tolerance), with further improvements in yield and cost reductions (Kalinina, et al., 2017; Hastings, et al., 2017; Lewandowski, et al., 2016). This requires a scaling up of investment in UK breeding efforts in association with industry. Areas which it has been suggested innovation should focus on include:

- Delivering cultivars which deliver greater biomass yield with minimal fertiliser inputs.
- Increased robustness of plants to increase potential for establishment success.
- Targeted regional adaptation to extend the geographic range for cultivation of *Miscanthus* genotypes further north and east in the UK and improve climate resilience (e.g. drought, frost and flood tolerance) (Kalinina, et al., 2017).
- Hybrids which can exploit land areas less suitable for food crop production e.g. marginal and contaminated land. This will require the development of stress tolerant novel hybrids.
- Varieties which will reduce pre-treatment costs for 2nd generation biofuels and bioproducts (Lewandowski, et al., 2016).
- Cultivars with high seed production for scaling up planting stock supply (Clifton-Brown, et al., 2018).
- Scalable and adapted harvesting, threshing and seed processing methods for producing high seed quality.
- Reduced costs of propagation to enhance scalability .e.g. plug-plants, micropropagation, direct sowing, Microencapsulation of stem and bud sections for planting using the “Crop expansion, encapsulation and delivery system" (CEED^{TM}) (Xue, et al., 2015).

There have been extensive programmes to improve breeding and propagation of Miscanthus in the UK and Europe focused on the development of seed-based hybrids planted as plug plants. This method of generating planting materials can potentially be scaled up to plant far greater land areas than the current technology of rhizome planting ((Clifton-Brown, et al., 2017); (Clifton-Brown, et al., 2018); (Lewandowski, et al., 2016); (Hastings, et al., 2017); (Xue, et al., 2015)). Historically, typical multiplication rates for rhizome planting were about 1:15 after three years, but industry stakeholders report that they are now typically about 1:20 after two years there are a number of innovations which could ensure that multiplication rates continue to improve.

Additional innovations proposed in stakeholder consultations include:

- The application of molecular approaches with further conventional breeding offers the potential for a second range of improved seeded hybrids.
- Development of non-invasive hybrids (infertile hybrids) to address concerns over potential invasiveness of *Miscanthus* as a non-native species.
- Strategies to significantly scale-up the production of planting materials (rhizomes or plug-plants). For example, development in the growing of *Miscanthus* rhizome or plug plant multiplication systems in controlled raised beds (like vegetables, parsnips/potatoes etc.) to enhance/increase rhizome yield and enable easier extraction of them.
- Development of storage systems for propagation material (rhizomes/cuttings) and treatments which can be applied to increase vigour, deter pests, and improve storage losses.
- Development of updated rhizome lifting, processing, storage, treatments, and transportation systems, and identify and trial any conditions/treatments which can maintain rhizome moisture content and vigour between preparation and planting.
- Improved access to cultivars from overseas for trialling under UK conditions.
- Application of vegetative propagation methods developed for sugar cane to *Miscanthus* cultivation.
- Development of on-farm propagation systems so farmers can establish their own small nursery plantation on-site and use this for scale-up.

2.5.2 Agronomic innovations in land preparation, planting and establishment

2.5.2.1 SRC

2.5.2.1.1 Weed control

Weed control has been identified as a critical factor in successful establishment. Weed control is currently heavily reliant on herbicides, with studies showing that mechanical weed control results in lower yields than chemical control (Larsen, et al., 2014). However, successful establishment of a productive SRC crop without herbicide use has been demonstrated using mechanical cultivation or cover crops (Albertsson, et al., 2016). Innovations proposed include:

- Further testing of automated, mechanical and robotic weeders to increase frequency and accuracy of weeding (Wynn, et al., 2016).
- Testing of cover crops for weed control to minimize or remove the need for pesticides (Albertsson, et al., 2016).
- More research on herbicides that can be used on energy crops would be beneficial to the cost-effective establishment of crops. Consideration could be given to how to make it easier for Extensions of Authorisation for Minor Use (EAMUs) to be transferred when herbicide and pesticide product names are changed (Wynn, et al., 2016).

2.5.2.1.2 Planting machinery

Potential improvements in planting machinery and automation have been identified in the literature with economic and environmental benefits but further work is needed to develop faster, more reliable and lower cost planting machines. Alternative establishment techniques with horizontal, as opposed to vertical, planting have been tested in the UK and in Sweden, and shown to reduce management costs considerably due to the use of similar equipment for planting and harvesting (Lowthe-Thomas, et al., 2010; McCracken, et al., 2010). One disadvantage is that the horizontal system requires more propagating material, which adds to costs. Therefore, it has not yet been widely adopted, although growth performance and survival rates in trials have been equally good or better than the conventional planting with horizontal cuttings (Phytoremedia, 2019).

Other areas for innovation include:

- determining optimal planting densities/ row spacing and how this varies with different varieties/clones/morphologies which could guide machinery innovation (Larsen, et al., 2019)
- optimisation of planting techniques and machinery innovation for use on marginal or contaminated land which have a range of additional challenges (e.g. (flood-prone, stony soils etc.).

2.5.2.1.3 Other innovations

Stakeholders expressed the view that there is inertia in the industry regarding the development of new machinery for planting and harvesting but that there are considerable gains to be achieved through machinery innovation in reducing establishment costs, which are a significant barrier to uptake. One area for innovation identified was to develop strategies for planting energy crops at different (non-spring) times of the year such as planting in the autumn under plastic. This would avoid issues with soil moisture, difficulty with spring ground preparations and would address the challenge of limited planting machinery by extending the planting window. Innovation is also needed to increase the precision/accuracy of planting to reduce gaps within plantations.

Stakeholders also suggested that land preparation, planting and establishment strategies more sensitive to environmental objectives could be developed by Natural England e.g. low till planting to reduce soil disturbance and soil carbon loss.

2.5.2.2 Miscanthus

A move to seed-based hybrids to significantly increase multiplication rates requires different planting and establishment strategies to rhizome planting. Direct sowing of *Miscanthus* seed is still challenging using current agronomy, with poor establishment rates. Recent efforts have focused on producing plug plants from seed-based hybrids under cover then planting out with mulch film. This establishment method is now achieving comparable yields to rhizomes, but is still the most challenging area for the mass deployment of seed-based hybrids (Clifton-Brown, et al., 2017). Potential innovations to further increase establishment rates, long-term yields, reduced costs and scalability described in recent reviews (Clifton-Brown, et al., 2017) include:

- Trials to produce plug plants for planting earlier in the year to increase yield and planting window.
- Alternative biodegradable mulch films to accelerate establishment; currently plastic films are used, resulting in soil contamination.
- Systems for planting plugs into the field are highly scalable using machines developed for the vegetable industry but need further development to make them suitable for planting on more marginal lands, especially those with high stone content.
- Further innovation in planting methods to improve establishment rates from direct sowing by hydroseeding and drilling (Anderson, et al., 2015).
- Weed control in the establishment phase is critical for maximising yield and is heavily reliant on pre-emergence and post-emergence herbicides (Smith, et al., 2015). The development of herbicide-free agronomy and associated machinery including robotics needs to be developed, for example using inter-row mowing and altered crop spacing.

- Multi-site trials to optimize agronomy for new cultivars and seed-based hybrids in different climatic and edaphic conditions including marginal and contaminated land.

Additional innovations proposed in stakeholder consultations include:

- Machinery development in automated rhizome planting and rhizome lifting systems.
- Development of automated plug plant planting systems, to increase planting speed and precision placement.
- Further development and testing of soil amendments to improve establishment on marginal and contaminated land e.g. biochar building on MISCOMAR research (MISCOMAR project, 2016).
- Development of herbicide-free agronomy for establishment and reversion including machinery innovation for inter-row mowing and testing whether altered timing of field operations during reversion could reduce the need for glyphosate.
- Pesticide development and trials including glyphosate replacement.
- Planting energy crops at different (non-spring) times of the year, to avoid issues with soil moisture and difficulty with spring ground preparations. Planting in the autumn under plastic or plastic substitutes for instance.

2.5.3 Agronomic innovation in crop management

2.5.3.1 Development of agronomic management strategies and protocols

Agronomic management strategies and protocols for new and current cultivars of SRCw and *Miscanthus* are needed which maximise productivity whilst reducing costs and GHG emissions.

- Multi-crop and multi-site trials of new varieties and cultivars, along with modelling and research on optimal management at cropping system level are needed to deliver this (Gabrielle, et al., 2014). This information would then feed into the development of detailed agronomic protocols for new cultivars and varieties in different climatic and edaphic conditions (Clifton-Brown, et al., 2018). The benefit of such a large programme would be to integrate testing of planting, establishment and management strategies that maximise yields and environmental benefits and minimise costs and GHG emissions (Richter, et al., 2016). These trials would enable the development of tailored protocols for particular varieties and environments, alongside testing and development of machinery innovations and assessment of environmental benefits.
- Optimising harvest time or rotation length is one area where innovation could maximise yield and feedstock quality in *Miscanthus* and SRCw. Further research is needed to optimise these strategies and incorporate this information into best practice agronomy guides. For *Miscanthus***,** harvest time can be optimized for yield, nutrient offtake and biomass combustion quality (Lewandowski, et al., 2016; Iqbal, et al., 2017). In SRCw, similar studies have been conducted which have demonstrated that the harvest cycle affects both yield and biomass quality with significant differences between five new cultivars tested (Stolarski, et al., 2011).

Additional innovations proposed in stakeholder consultations include:

- Machinery/automation to increase efficiency/precision of fertiliser applications.
- Government funded plantations should be established as part of a National Centre for Energy Crops, this would provide demonstration capacity and build confidence with growers and farm influencers and be a location for R&D aspects.
- Multi-site variety trials should be used to assess risks of pest and disease resistance in new varieties of *Miscanthus* and SRCw and also develop best practice.
- Trial work with pest deterrent sprays (e.g. Grazers™, Garlic Barrier™).
- Long term fertiliser information trials for both micro and macro elements.

2.5.3.2 Diagnostic and predictive tools for bioenergy crop yield

Innovations in predictive and diagnostic tools to improve crop productivity and efficiency have great potential. Two studies have reported the use of remote sensing to maximise bioenergy crop productivity (Richter, et al., 2016; Ahamed, et al., 2011). For example, in the UK, medium and light textured soils have more predictable yields than heavy soils. However, heavy soils have greatest yields, though this comes with the highest uncertainty. Information of this type can be used to improve agronomic practice on difficult sites but needs spatial tools to interpret this information at a field or landscape scale (Richter, et al., 2016).

These techniques could be used to monitor crops in real-time to allow targeted interventions, but remote sensing techniques need to be further developed and tested across multiple sites and crops to determine their effectiveness in increasing yields and decreasing costs.

Drones are also being developed to record the volume and vigour of biomass plantations to inform management and harvesting and supply logistics[4]

2.5.3.3 Crop removal or re-planting

End of life crop removal strategies need further research and testing to understand the economic and environmental impacts, particularly for mature SRC plantations (McCalmont, et al., 2018). Methods tested experimentally for SRCw and *Miscanthus* reversion using herbicides, fallow periods and follow-on crops to mop up nutrients (McCalmont, et al., 2018) and investigated across a limited number of reverted sites, have demonstrated varied impacts on nitrous oxide emissions and soil carbon stocks. This research needs extending to more mature crops at commercial scale to develop and test alternative crop removal protocols which minimise impacts on GHGs, soil carbon and soil quality more generally, while successfully reverting the land. Strategies which do not use pesticides should be included in this work for use on organic farms or in a future farming environment which may not have access to total herbicides or graminicides (Croxton, 2019).

Removal of SRCw and *Miscanthus* has been successfully achieved across Europe and in the UK but there are still perceptions by potential growers that this is difficult and that growing SRCw will damage land drains and affect land values. Evidence indicates that land values are unaffected by energy cropping with values based on the land's productive capacity, but this barrier needs to be addressed through information supply (Energy Technologies Institute, 2016). Strategies for crop removal could, for example, be videoed to demonstrate the ease and timescale of removals. Demonstration of this could be included within any online information resource e.g. time-lapse filming to show methods of removal with and without herbicides.

2.5.4 Harvesting and processing innovation

A lack of R&D funding over the last 10-15 years for machinery and plant protection products for energy crops was identified in the literature and from stakeholder consultation (Wynn, et al., 2016). Significant funds were invested by Bical for SRCw in the past, but this learning has not been translated into practice (Wynn, et al., 2016; Croxton, 2019).

2.5.4.1 SRC

A number of papers have described the development and testing of harvesting machinery and methods for SRC poplar and willow which broadly comprise cut and chip versus harvest and storage (Vanbeveren, et al., 2018) (Vanbeveren, et al., 2017; Vanbeveren, et al., 2015; Berhongaray, et al., 2013; Santangelo, et al., 2015). The direct chipping method has the highest capacity, but it also has highest fuel consumption (Vanbeveren, et al., 2017). Potential areas for further research and innovation identified in the literature include:

[4] http://biofuel.iggesund.co.uk/?s=unmanned+

- cutting heads and harvesting techniques developed in Sweden (Ricardo, 2020) which look to be applicable to the UK context
- Understanding interactions between harvest time, rotation length and machinery requirements need (Santangelo, et al., 2015) and using existing research on the effects of harvest intervals on yield to guide machinery innovation (Larsen, et al., 2019).
- Harvesting efficiency also varies with plant genotype, stocking density, row spacing and headland size, therefore interactions between planting strategies and harvesting need to be accounted for in developing harvesting machinery and agronomic strategies (Vanbeveren, et al., 2018; Larsen, et al., 2019; Vanbeveren, et al., 2017).
- Design, testing and bring to market reasonably priced SRC machinery that can be applied to marginal areas such as small fields, wet soils and sloping fields or for winter harvesting (Wynn, et al., 2016).
- The development of mobile pelleting machinery is still in its infancy. An affordable unit capable of producing quality pellets on farms is required (Wynn, et al., 2016).

Additional innovations proposed in stakeholder consultations include:

- A shorter 2-year rotation length may be possible with improved agronomy/precision farming and would allow smaller harvesting machinery to be used reducing soil damage and GHG emissions. This needs trialling.
- Machinery innovation to enable winter harvesting of SRCw at wet sites would result in a harvest that is less stressful to the plant and produces biomass with a lower moisture content, which is beneficial for the processing and end-use and would reduce damage to soil structure. Track based machinery is being trialled in Sweden which could be appropriate.
- The consequences for yield of variable harvest time-points need further testing through trials or accessing data from commercial farms and potentially modelling.

2.5.4.2 Miscanthus

A number of papers have described the development and testing of harvesting machinery and methods for *Miscanthus* including direct chipping harvesters, baling technology and pelleting, with the goal of decreasing costs and increasing the speed of harvesting (Mathanker & Hansen, 2015; Mathanker, et al., 2014a; Mathanker, et al., 2014b; Morandi, et al., 2016; Lewandowski, et al., 2016). Lewandowski, et al. (2016) stated development of agricultural equipment for *Miscanthus* production is one of the two most important areas where technological advances can be made for *Miscanthus* (with breeding programmes being the other). Potential innovations include developments in the design of cutting blades and cutting speed, which have implications for harvest yield and the energy efficiency of harvesting of *Miscanthus* e.g. straight, angled or serrated blades (Gan, et al., 2018).

Additional innovations proposed in stakeholder consultations include:

- Further advances in baling technology to increase density of bales and reduce costs
- Baling of chipped material needs evaluating, potential advantages for bale density but unknown consequences e.g. heating degradation etc. This has been briefly investigated by Nova Biom, France who evaluated direct chipping in a net baler in the field with positive results reported.
- Trialling harvesting in November, trade-offs in yield, feedstock quality, harvest.

2.5.4.3 On-farm pre-processing

On farm pre-processing innovations were not identified from the academic literature review but were raised by stakeholders in the consultation. On farm pre-treatments can potentially deliver feedstocks that are easier to handle, easier to store, are dry, low in problematic ash, low in alkali metal salts, halides etc. Proposed innovations which need further investigation include:

- On-farm compaction or conversion into more energy dense forms, for example torrefaction followed by pelleting.
- On-farm washing or natural leaching to improve product characteristics ready for combustion/gasification.

2.5.4.4 Biomass storage

Poor biomass storage can have a significant influence on the economics of energy crop cultivation (Sahoo, et al., 2018), as any losses of biomass or degradation in the quality of the biomass during storage will reduce its value. On farm harvest-optimised storage systems need to be developed to supply wood chip at the correct moisture content and avoid contamination and degradation (Lenz, et al., 2015). ETI investigated impacts of storage on *Miscanthus* quality but the study was limited and needs expanding for both SRCw and *Miscanthus* (Forest Research/ Uniper, 2016a). This has also been investigated in a US study of wood chip and pellet storage which concluded that different options were optimal depending on the length of time biomass was being stored, which is dependent on the supply-chain (Sahoo, et al., 2018).

Additional innovations proposed in stakeholder consultations include on farm storage improvements. For example, large capacity on-farm bale storage will be needed if thousands of hectares, or millions of hectares, are planted. For *Miscanthus* this could involve collaboration with industry already involved in on-farm storage solutions for traditional straw bales. Development of a rapid bale stack covering system that does not include the use large sheets placed over the top of stacks, which is a significant health and safety risk, was also suggested. (Stakeholder, 2019).

2.5.5 Land use innovation to harness the environmental benefits of energy crops

Energy crop cultivation can also have a number of environmental benefits and a full understanding of these by farmers and other producers, can help to encourage their cultivation and lead to increased production. Innovations in this area of environmental benefits could therefore help to support other innovations discussed above which are designed to improve profitability and reduce risk.

2.5.5.1 Energy crop planting on contaminated or urban land

Perennial bioenergy crops including SRC willow, *Miscanthus* and Reed Canary grass have potential to be used for phytostabilization, phytodegradation and/or phytoextraction of organic and inorganic pollutants on contaminated or brownfield land with potential environmental and socio-economic benefits delivered alongside the production of bioenergy feedstocks, but there are significant challenges in achieving economic yields on these sites.

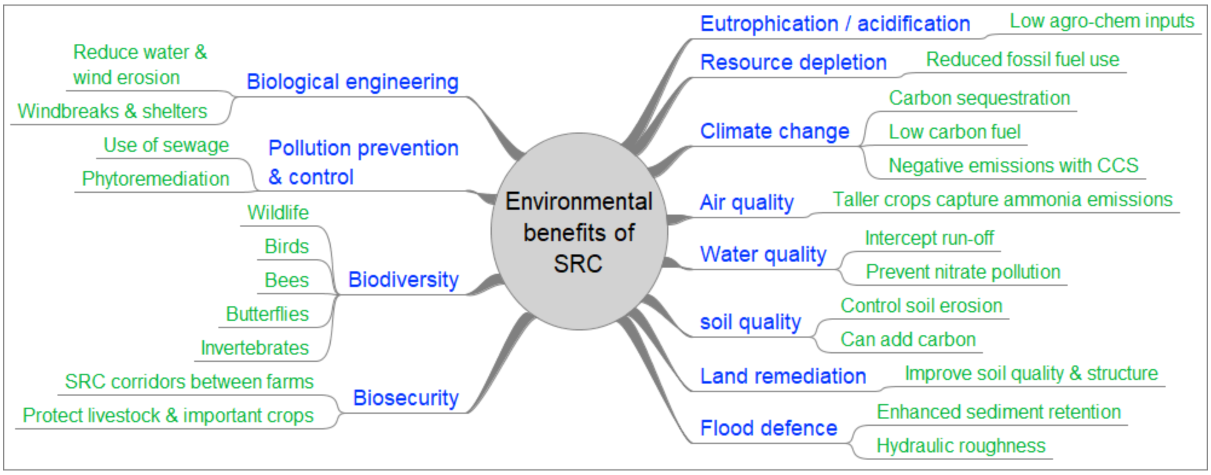
Further research is needed to identify appropriate hybrids/varieties of SRC willow, *Miscanthus* and Reed Canary grass for particular pollutants, which can either phytoextract contaminants or grow robustly on contaminated land, tolerating the typically harsh edaphic conditions including low nutrients, poor soil quality and the presence of toxic elements. In addition the economics and environmental risks from the application of these technologies need to be quantified (Rowe, et al., 2009) (Ruttens, et al., 2011).

2.5.5.2 Multi-functional land use innovations

Producing energy crops on contaminated or urban land or agricultural land that is marginal for food production is likely to be economically challenging if the crops are only valued on their yield. Energy crops contribute a wide range of ecosystem services, which have value to landowners and managers, local communities and the wider environment. These are summarised in Figure 2-12. The value for society includes many ecosystem benefits: the effects of a return to perennial crop cover that protects soils, potential increases in soil carbon storage, the protection of vulnerable land or the cultivation of polluted soils and the reductions in GHG emissions (Lewandowski, 2016). There is strong evidence that the multi-functional potential of energy crops is being under exploited (Adams & Lindegaard, 2016). There is a growing body of evidence in this area, but a number of innovations are needed to ensure that the multi-functional value of energy crops can be used as a tool to increase the uptake of energy crops by growers.

Data innovation is needed to better understand, assess and value the multi-functional benefits of energy crops in different localities to better inform potential growers and to inform policy development (Adams & Lindegaard, 2016). There is strong scientific evidence of the multi-functional benefits of energy crops in the UK, but this data needs to be incorporated into scenario modelling tools or decision-support tools to inform growers and policymakers designing agricultural support schemes.

Figure 2-12: Summary of the potential multi-functional environmental benefits of Short Rotation Coppice Willow



Source: adapted from (Adams & Lindegaard, 2016)

Landscape and farm-scale integration of energy crops: The delivery of a range of ecosystem services is affected by energy crop cultivation. Innovations proposed focus on how multi-functional land use could be implemented at a landscape and farm-level. For example, a range of papers describe how site characterization and field-scale design could be used to incorporate biomass production into agricultural cropping systems to deliver multiple environmental objectives and improve overall farm productivity through nutrient efficiency, biodiversity enhancement and reduced agrochemical losses (Ssegane, et al., 2015; Ssegane, et al., 2016; Bunzel, et al., 2014; Gabrielle, et al., 2014). In the UK, a number of whole-farm integration case studies have been described (Energy Technologies Institute, 2016). Innovations proposed include:

- Assessment of economic and environmental performance of landscape strips and buffer strips planted along arable field margins and watercourses (Ferrarini, et al., 2017).
- Testing of planting designs and management strategies which use energy crops as part of the management of nitrogen in agricultural systems (Skenhall, et al., 2013).
- Cost-benefit analysis of multifunctional environmental and socio-economic benefits of energy crops (Wynn, et al., 2016).
- Assessment of integration of energy crop cultivation into rotational management of land (Gabrielle, et al., 2014).
- Further assessment of management strategies and environmental benefits of using urban land for SRC planting (McHugh, et al., 2015).
- Landscape planning tools are needed to provide predictions of impacts of crop establishment across scales from individual fields, through farms to whole catchments or regions.

If implemented these innovations could:

- Enable the value of these benefits to be quantified and explained to potential growers.

- Enable this information to be integrated into land use planning at regional, local and farm-scale to increase sustainability.
- Inform any future agricultural subsidy or support scheme.

Additional innovations proposed in stakeholder consultations include:

- Development of planting and management strategies to support environmental objectives for example to encourage planting on Natural England farms.
- The need to help farmers understand the package of environmental benefits that energy crops can bring to a farm.

Management strategies for specific environmental objectives:

Flood mitigation: SRC has the potential to provide flood mitigation benefits. While there is limited evidence in the academic literature, there is support from industry case studies and an Environment Agency study (Environment Agency, 2015). There is a need for new evidence to demonstrate where planting energy crops could deliver flood mitigation benefits, the value to the local environment of reduced flood risk and how the co-benefits of flood mitigation and energy crop production be best optimised so that costs of harvest are not too great while flood protection benefit is maximised. Specific innovations include:

- Planting onto flood prone land may have implications for management and harvesting, requiring the development of suitable harvesting equipment to travel on waterlogged ground.
- Innovation around altering harvest times around flood periods for alternative end-uses.
- An assessment of the flood mitigation potential on a catchment basis. This could be assessed through site-specific modelling in the UK for selected watersheds/catchments.
- Mechanisms for assisting planning to maximize this benefit are currently not available. However, there is potential for this to be achieved using available data such as flood risk maps and crop yield maps.

Water availability: There is a knowledge gap regarding the potential effects of bioenergy expansion on water availability across the UK. Extending high-resolution modelling to the whole of the UK is possible as necessary data on land cover, rivers and catchments are available, and would enable informed decision making on the impacts of planting at different scales and locations (Holder, et al., 2019). This could allow targeted planting at a landscape/catchment scale to maximise GHG, economic and environmental benefits while limiting any negative impacts.

Cleaning up contaminated water and land: Energy crops have been demonstrated to be effective bio-filtration systems. They are particularly well suited and cost-effective option for dealing with low volumes of wastewater produced by small rural communities and dealing with landfill leachates, industrial effluents and remediating heavy metal contaminated sites (Wynn, et al., 2016). Energy crops can also help to remediate contaminated land (see section 2.5.5.1).

Biodiversity: There are potential benefits of energy crops for biodiversity, but these depend on how plantations are located within the landscape or farm and the scale of planting. Management strategies to increase biodiversity including planting design and farm-scale integration have been assessed in a range of studies (Gabrielle, et al., 2014). This information needs to be incorporated into agronomic guidance and valued through cost-benefit analysis to inform growers, policy and support development.

Pollination services: SRCw produces large amounts of nectar and pollen in the early months of the year. The majority of willows produce catkins in the lean late winter and early spring months when there are few other abundant sources of pollen or nectar available in the countryside. The value of these pollination services to other agricultural crops need to be quantified to contribute to the broader valuation of ecosystem services from energy crops (Berkley, et al., 2018) (Stanley & Stout, 2013) (Wynn, et al., 2016).

The importance of valuing multi-functional benefits of energy crops and assessing the optimal way to integrate energy crops in the landscape was strongly emphasised by stakeholders in the consultation interviews with support for payment/subsidy schemes which recognise and reward these benefits.

Additional innovations proposed in stakeholder consultations include:

- Development of landscape strips to enhance connectivity for biodiversity.
- Buffer strips for environmental goals e.g. nutrient management or biodiversity.
- Willow breeding results in a female sex bias, so most current SRC varieties are female (only produce nectar). SRC plantations could support pollinators if a mixture of varieties containing more male varieties (pollen and nectar) are grown that are tailored to flower at a specific time that would be most beneficial to pollinators. This alternative planting strategy needs evaluating but could be valuable early in the season when pollen resources are scarce (see section 2.5.1.1).
- Development/inclusion in Game cover-crops and agro-forestry development.
- Test the potential to use energy crops to improve soil compaction and water run off risk near highways.

2.5.6 Innovations in information supply and engagement to address barriers to uptake

Many of the potential innovations described in this Section of the report, lie outside the scope of a technology focused innovation programme (as discussed further in Section 5.1). However, as stakeholder felt strongly that improved information and advice could make a substantive contribution to future increases in feedstock planting, a discussion of these innovations is included here for completeness.

2.5.6.1 Support and resources for landowners/managers

The lack of a dedicated single, independent source of information and support for growers has been identified as a barrier to uptake and recommended by a number of studies and stakeholder consultations, for example (Wynn, et al., 2016) (Whitaker, 2018). This central information resource should provide an online planning and information resource. Areas identified for inclusion previous work on expanding supply of energy crops (Wynn, et al., 2016) and by stakeholders include:

- Financial guidance to ensure growers are accurately informed about the profitability, cashflow and risks of energy crops.
- Updated best practice guidelines including nutrient management guidance (Croxton, 2015; Croxton, 2014).
- Current information on land conversion procedures for energy crops with specific information on EIA procedures, statutory consultations prior to planting, CAP/other protocols and sustainability requirements of renewable energy schemes (Wynn, et al., 2016).
- Independent advisors and contractors' database for energy crop specific services.
- Provision of independent, impartial feasibility advice. An example of this was a scheme under the Rural Development Plan, Resource Efficiency for Farms (R4F) run by Rural Focus, a subsidiary of Business Link (BL) which ran from 2009-2013.
- Accredited training courses need developing for farmers, contractors and advisors. Information materials could also be developed for agricultural college courses to encourage new entrants.
- A planning tool whereby farmers can put in their own figures, land area, land type and other data to get a first pass "look-see" as to how energy crops might work for them.

Other proposals from the (Energy Technologies Institute, 2016) include:

- An industry led energy crops levy board to make the sector more competitive by increasing the availability of impartial information and facilitating applied research.

- Advice made available through agricultural extension workers similar to the Resource Efficiency for Farms (R4F) scheme. Knowledge Transfer Groups could be set up for energy crop growers and prospective growers using Rural Development funding.

Additional innovations proposed in stakeholder consultations included a National Energy Crops Centre as a central, independent source of information and expertise for farmers/grower focused on energy crops. This idea was strongly supported by all stakeholders consulted, where it was viewed as critical if substantial upscaling of energy crop cultivation is to be achieved. Proposed activities included:

- Development of readily available on farm economic models for farmers/influencers to see and use, when comparing annual crops against perennial energy crop plantations.
- Encourage and provide funding support systems for farmers to build local cooperative groups where the cooperative can manage a volume of energy crops and move tonnages that are most at risk of arson, vandalism, or rotting.
- A pesticide register for farmers to use – there is currently a lack of available information easy to hand. Only poor information is available on which pesticides can be legally applied to *Miscanthus* and SRC. Similarly, only poor information is available regarding fertiliser requirements for the post planting phase.
- A recommended varieties list for energy crops, as is available for other agricultural crops, which should include yield, pest and disease resistance, sex, senescence date, bud burst and flood or drought resilience.
- Agronomic research funding.
- Development and understanding of the commercial scale requirements for delivering 100,000ha of energy crop plantings every year, from a standing start in 2022.

2.5.6.2 Engagement and promotion

Energy crops need to be more widely promoted throughout the supply chain and in local communities to encourage uptake and provide accurate, robust and respected information. Areas highlighted in the literature include engagement with agrochemical companies, farm machinery suppliers, land agents, agricultural advisors, NFU etc. These organisations are significant influencers and need to be utilised in order to develop the crops and help promote them to the farmer (Wynn, et al., 2016; Croxton, 2019). Engagement with local communities to address any negative viewpoints on bioenergy and biofuels in areas where energy crops could be planted. This needs to include information on the benefits of large-scale use of biomass in power stations, which tends to be viewed more negatively than local use of biomass.

2.5.6.3 Economic innovations

Stakeholders consulted suggested that without end-to-end policy support, technical innovations will not deliver the desired upscaling in supply, and outcomes will be sub-optimal. Support for growers to establish crops, and incentives for end-users to use the produced biomass need to be established in tandem so supply matches and is stimulated by demand (Stakeholder, 2019). Economic innovations identified in the literature include:

- LEPs and other regional enterprise agencies could be encouraged to conduct feasibility studies to identify suitable locations for pilot projects (Wynn, et al., 2016).
- Rural Development funds (LEP Growth fund, LEADER funds via LAGS) could be channelled into forming local initiatives such as producer groups with supply hubs to support these opportunities alongside establishment grants i.e. form local initiatives and co-ops (Wynn, et al., 2016).
- Capital grants offered through Rural Development Programmes (RDP) could include energy crop machinery in addition to forestry kit (Wynn, et al., 2016).

2.5.7 Summary of innovations in energy crop supply chain

A wide range of potential innovations were collated from the literature review and stakeholder consultations, spanning the full spectrum of energy crop production processes. This diversity reflects the early maturity of the energy crops sector in comparison to the well-established forestry sector. Table 2-6 summarises the key innovations and identifies the challenges or barriers which they address. It is likely that any innovation competitions would need to ensure that an integrated approach was taken to ensure that the all aspects of the supply chain were considered if individual innovations are to fully deliver potential improvements across the whole supply chain.

Table 2-6: Summary of innovations addressing identified challenges and barriers

Challenge /barrier	Crop[a]	Innovations
Increasing yield and resilience in new varieties	M	Breeding/screening for cultivars with improved traits for yield, climate and stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including multi-site trials to test traits of interest
	S	Apply molecular tools to speed up breeding/screening for range of traits: improved yield, climate and stress resilience (drought, flood, frost, marginal land), growth on contaminated land.
Scaling up production of planting materials	M	Cultivars with high seed production for scaling up
	M	Adapted machinery methods for *Miscanthus* seed production
	M	Improved propagation methods to reduce costs, increase scalability and improve establishment success
	M	Improved storage systems and treatments for propagation material
	M	Improved rhizome production, storage and transportation to maintain vigour
	S	Production sites for planting material need scaling up alongside innovative method development e.g. micropropagation
Planting machinery innovations to increase establishment success and productivity	M	Machinery, strategies for planting plug-plants to increase establishment success, widen planting window and reduce environmental impact e.g. biodegradable films (not plastic), automated planting systems
	M	Seed-treatments, agronomy and machinery for direct-sowing of *Miscanthus* seed
	M	Machinery development for automated rhizome planting
	M	Joint development of agronomic machinery in tandem with novel varieties and agronomic strategies to maximise yield and cost and GHG savings
	S	Planting machinery improvements combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land.
Increased establishment success and expansion of planting window	S	Breeding for traits to increase planting success e.g. delayed bud-burst
	M/S	Weed control: herbicide-free agronomy, cover crops, machinery development and testing e.g. mechanical and robotic weeders
	M	Developing strategies to plant at different times of year (non-spring) e.g. autumn planting under plastic
	M	Development and testing of soil amendments for marginal or contaminated land
Development of new pesticides	M/S	Herbicide development and trials
	M/S	Pesticide development and testing combined with new cultivars with pest and disease resistance traits.

Challenge /barrier	Crop[a]	Innovations
Innovations in harvesting machinery to improve efficiency and access to difficult sites	M/S	Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs
	M/S	Development and testing of harvesting machinery with new varieties, harvest times, rotation lengths
	M	Baling technology: improvement to increase bale density so reducing costs and evaluation of baling chipped material
	S	Machinery development for marginal areas (small, wet or sloping sites) and for winter harvesting at wet sites e.g. track-based machinery.
	S	Development of mobile on-farm pelleting
	M/S	On-farm pre-processing needs R&D to design and test strategies and processes e.g. on-farm compaction or washing/leaching to improve feedstock combustion quality.
Increasing knowledge on optimal harvesting	M/S	Research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality
	S	Breeding for traits to widen the harvesting window including multi-site trials for traits of interest
	S	Information needed on long-term yield effects of harvesting outside the winter dormant window to inform to growers and contractors.
Deterioration of during storage	M/S	Development of optimised storage systems including on-farm storage to prevent deterioration and maximise feedstock quality and scale-up storage facilities
Monitoring to improve yield and reduce costs	M/S	Development of diagnostic and predictive tools to increase yield e.g. soil mapping to predict yield and remote sensing/drones to monitor in-field crop vigour to inform management and harvesting.
Concerns over difficulties with crop removal	M/S	End-of-life crop removal or re-planting strategies have been investigated at small-scale but strategies need developing to minimise impacts on soil carbon and GHGs, including herbicide-free strategies. Successful strategies need demonstrating to growers.
Diversification of market	S	Production of high-value industrial compounds and feedstock for energy combustion have been identified but needs further R&D to develop commercial processing systems and identify best-practice agronomy and varieties
Updated guidance for growers	M/S	Development of best practice guidance with management strategies for new and current cultivars requires multi-crop and multi-site trials for different climatic and edaphic conditions
	M/S	Fertiliser information and trials for micro and macro elements
	M/S	Pesticide register
	M/S	Varieties list

Challenge /barrier	Crop[a]	Innovations
Supply of robust, independent Information and advice	M/S	Central, independent source of information and support for growers. To include provision of economic and planning tools and support, best practice guidelines, training, independent advice; would also engage with influential stakeholder groups.
	M/S	Energy crops levy board
	M/S	Development of recommended varieties lists as for other agricultural crops
	M/S	Pesticide register
Land use innovation to enable growers to benefit from multifunctional benefits of energy crops	M/S	Identify hybrids/varieties to grow robustly on contaminated and/or urban land and develop and test soil amendments to improve establishment and yields on contaminated and/or urban sites
	M/S	Assessment of farm-scale integration of energy crops in order to inform growers with site-selection. Practical testing of landscape/buffer strips, role in nitrogen management, rotational management
	M/S	Develop decision-support tools to inform growers of multifunctional benefits of energy crops in specific locations
	M/S	Develop landscape or scenario-modelling tools to predict environmental benefits/impacts of bioenergy crops at range of scales, farm, catchment, region. For example, assessment of flood mitigation potential on a catchment basis; impacts of planting on water availability.
	S	Develop agronomic guidance and knowledge to support growers in benefiting from multi-functional benefits of energy crops. Flood mitigation: machinery development and testing altered harvest times to accommodate flood periods. Biodiversity: incorporate research evidence into agronomic guidance to inform growers in site-selection and management Pollination: Willow breeding and planting to increase pollen and nectar from male varieties
Lack of awareness	M/S	National centre to coordinate engagement with wide range of stakeholders with influence e.g. agrochemical companies, land agents and general public
Economic	M/S	A range of economic innovations proposed involving Local Enterprise partnerships and Rural Development Funds to build capacity, fund pilot projects or provide capital grants for machinery.

Note:[a] M = *Miscanthus;* S = Short rotation coppice

3 Forestry

In this report we use long rotation forestry (LRF) as a term to distinguish typical forest management practices, where trees are primarily grown for timber and are allowed to mature over a long period, typically forty to one hundred years. Wood for bioenergy purposes in long rotation forestry typically arises from early pre-commercial thinnings. The term short rotation forestry is used to describe the cultivation of fast-growing species at planting densities that allow significant biomass yield to be obtained over a timescale of ten to twenty-five years.

3.1 Conventional long rotation forestry

3.1.1 Production

The main steps in the production of biomass in forestry (up to the point where the biomass is ready for removal from the forest) for coniferous plantations and also broadleaved woodlands where they are managed for economic purposes are outlined in Table3-1. They reflect typical current practice.

Table3-1: Key steps in production of biomass from conventional forestry

Step	Description
Planting stock preparation	The planting material might be seedlings or rooted cuttings. In some nurseries the seedlings and cuttings can be grown in containers and then, before dispatch from the nursery, plants are removed from their containers, graded, bundled and the roots wrapped in 'clingfilm' ready for transport to the forest planting site. Alternatively, where seedlings and cuttings are grown in an open nursery, plants are lifted, graded, bundled and bagged for transport. Planting stock preparation includes considerable nursery work in addition to these end of cycle steps, e.g. sowing and irrigation, fertilisation, and spraying are all required, and it typically takes 2 to 4 years to produce the planting material from seed depending on the species. In some cases, rather than using plants, seed is sown on prepared planting positions in the forest (referred to as direct seeding).
Ground (site) preparation	This consists of bringing the planting site to the condition where it is ready for the planting process to be undertaken. Processes potentially involved include drainage, some fencing, mounding or ploughing. In a very small number of cases, this might involve the removal of some or all material from the previous crop, such as harvested stumps or stools for phytosanitary reasons.
Planting and establishment	Planting may involve some application of herbicide to minimize competition from weeds during establishment of the young crop. In occasional cases it might include the use of natural or artificial fertilizer. If there is high initial mortality, replacement plants may need to be planted, an operation known as 'beating up'. Different planting approaches (natural regeneration, direct seeding, individual planting of seedlings) differ considerably in how much input is required.
Maintenance	Management is most intensive in the early stage as the crop becomes established; it is important to get it to a point where it is free to grow, i.e. not constrained by vegetation competition or damage from browsing mammals or insects. It may include further applications of herbicide, pesticide and possibly fertilizer. Once the tree canopies close further interventions are seldom required, except in the case of pest or pathogen attack.

Step	Description
Thinning	In order to promote rapid canopy closure and good form of the young trees (i.e. tall and straight, with minimal side branches), commercial forests are normally planted at relatively high stem density. Thinning, typically starting at around 15 to 20 years and then every five years or so, is used to remove a small proportion of the stems to cut down tree-tree competition and allow the others to thrive. Early (or pre-commercial) thinning produces almost no sawlog quality timber, so the material removed has little commercial value as timber but can be used for bioenergy if there is a market for it. Thinnings from older crops have a market value as fence posts, and for use in engineered wood products such as chip board, and potentially bioenergy.
Harvesting	The equipment required will depend on the size and nature of the material to be harvested. On some sites, heavy harvesting machinery can cause soil damage through compaction, so a proportion of the side branches and tops of the harvested trees are arranged in rows (brash mats) to form routes where the soil is protected. This harvesting step will provide mainly sawlogs although some smaller diameter material e.g. side branches and tops may be suitable for bioenergy
Storage and pre-processing	In many cases this will only include stacking logs, cut to length, at roadside, however it may include chipping or, in the case of relatively fine brash, compressing into bundles and binding into bales for ease of handling and transport.
End of life/reversion	In the case of a forestry crop, irrespective of its end use (for timber, pulp or bioenergy) there is an obligation to replant, and reversion to the original land use is only possible in rare cases where there is an environmental justification.

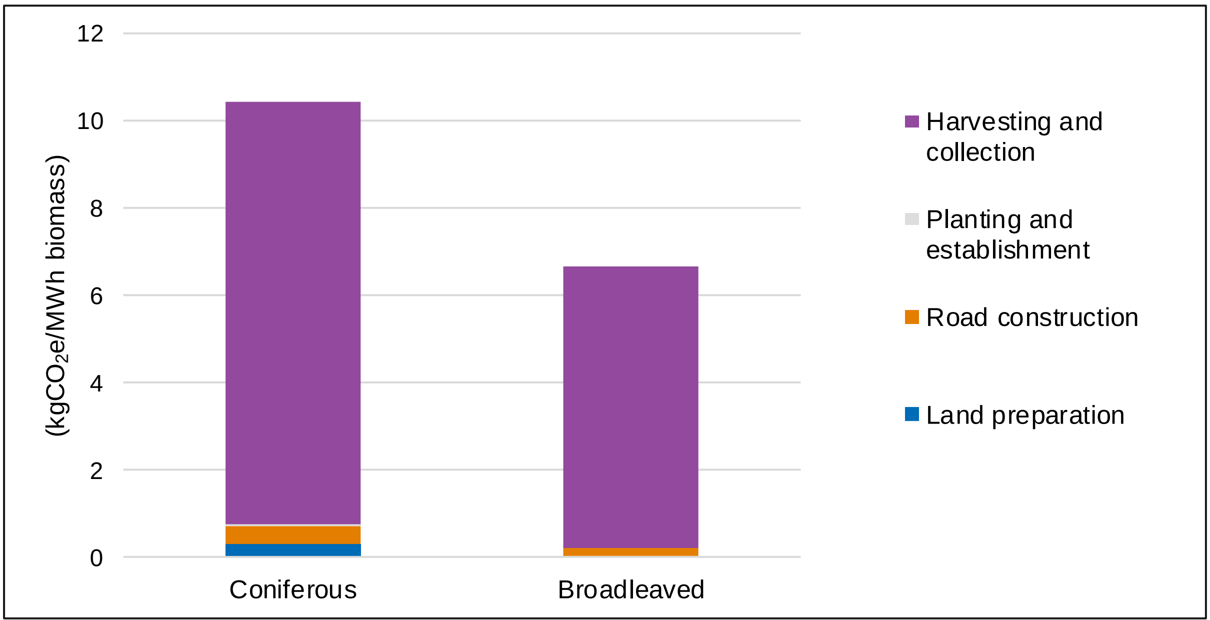
3.1.2 Greenhouse gas emissions from LRF

A full evaluation of the net GHG flux associated with production of timber for bioenergy from conventional forestry is complex, as it requires evaluating changes in the carbon stock of the forest itself including trees, litter and soil, and carbon in not just wood removed from the forest for bioenergy, but also wood removed for other uses. For some of these other uses, e.g. saw logs for construction, carbon may be stored up in the products for many years, whereas in wood removed for bioenergy the carbon in the wood is released immediately on combustion of the wood. An absolute evaluation of the carbon benefits of producing wood for bioenergy also requires consideration of the 'counterfactuals' i.e. what would have happened in the forest if there were no production of bioenergy from wood, and the carbon impacts of replacing other wood products from the forest with and alternative (e.g. using steel or concrete in construction rather than timber). Choices about the counterfactual can have a significant impact on the overall net carbon flux of using wood for bioenergy as discussed for example in (Stephenson & MacKay, 2014) and (North Energy, Forest Research and NNFCC, 2018).

Such a full evaluation is difficult in the context of this study due to the narrow boundary of the assessment, from planting to forest road, which excludes examination of the uses of other forest products to determine their impact on carbon stock levels. The focus of identifying GHG emissions associated with production is to allow an assessment of the impact of innovations on GHG emissions from each process step. The assessment of GHG emissions here is therefore limited to emissions directly related to planting, establishment and harvesting of wood for bioenergy.

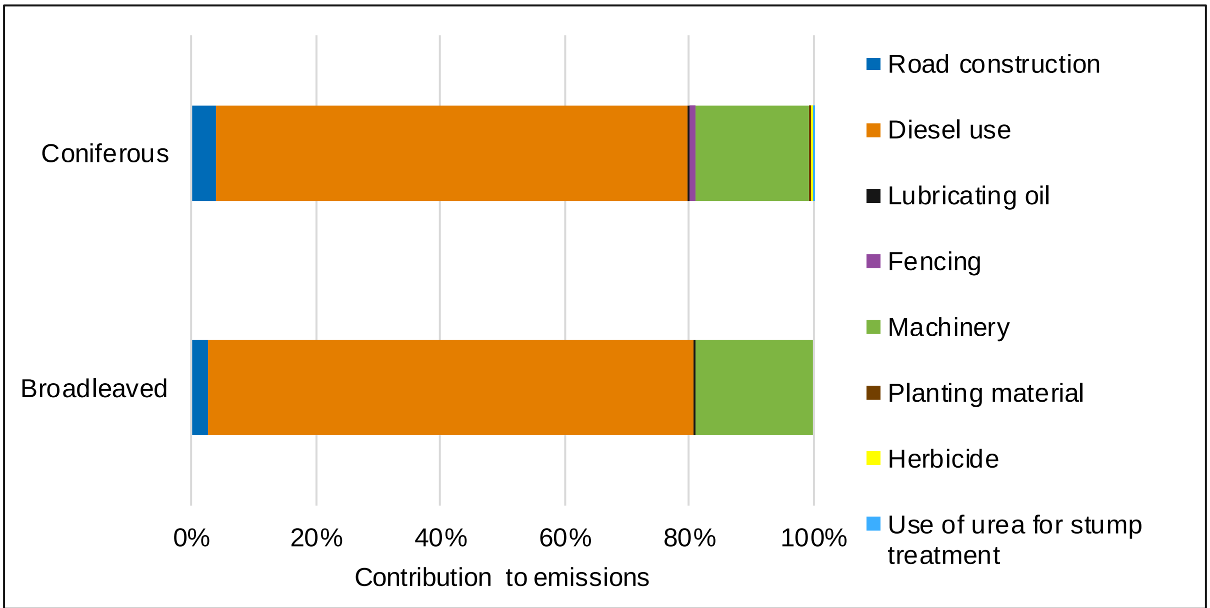
These are shown for coniferous and broadleaved forests in Figure 3-1, and as for energy crops are derived from data in (North Energy, Forest Research and NNFCC, 2018). They reflect the original assumptions in that report, i.e. that wood from coniferous forests comes from forests planted commercially (so all process steps over the forest lifecycle are considered) but that in the case of broadleaved forests, wood comes from increased management within an existing forest, so that only thinning of the forest to produce wood suitable for bioenergy is considered in the analysis, i.e. planting and establishment are excluded. The results for coniferous forests suggest however that this stage is responsible for only a small proportion of emissions and that the predominant source of emissions in both types of forest is harvesting, with the main contributing factor to this being diesel use (Figure 3-2). The other significant source is the production of machinery used for forestry operations.

Figure 3-1: GHG emissions by process step from production of wood for bioenergy in LRF



Source: derived from (North Energy, Forest Research and NNFCC, 2018). Includes emissions up to forest road only; emissions from transport and processing away from the forest are excluded

Figure 3-2: Sources of GHG emissions in production of wood for bioenergy in LRF



Source: derived from (North Energy, Forest Research and NNFCC, 2018). Includes emissions up to forest road only; emissions from transport and processing away from the forest are excluded

3.1.3 Costs of long rotation forestry

There are many factors that influence the cost of production, including:

- The scale of the operation.
- Geographical characteristics such as: slope, soil type and quality, the requirement for draining.
- Biological factors such as the presence of a significant deer population, the need to control other pests such as *Hylobius abietis*, and the necessity for repeated herbicide applications.
- Operational factors such as whether it is new planting or a restocking, choice of ground preparation technique, planting material used, planting density, and the requirement to replace failed seedlings.

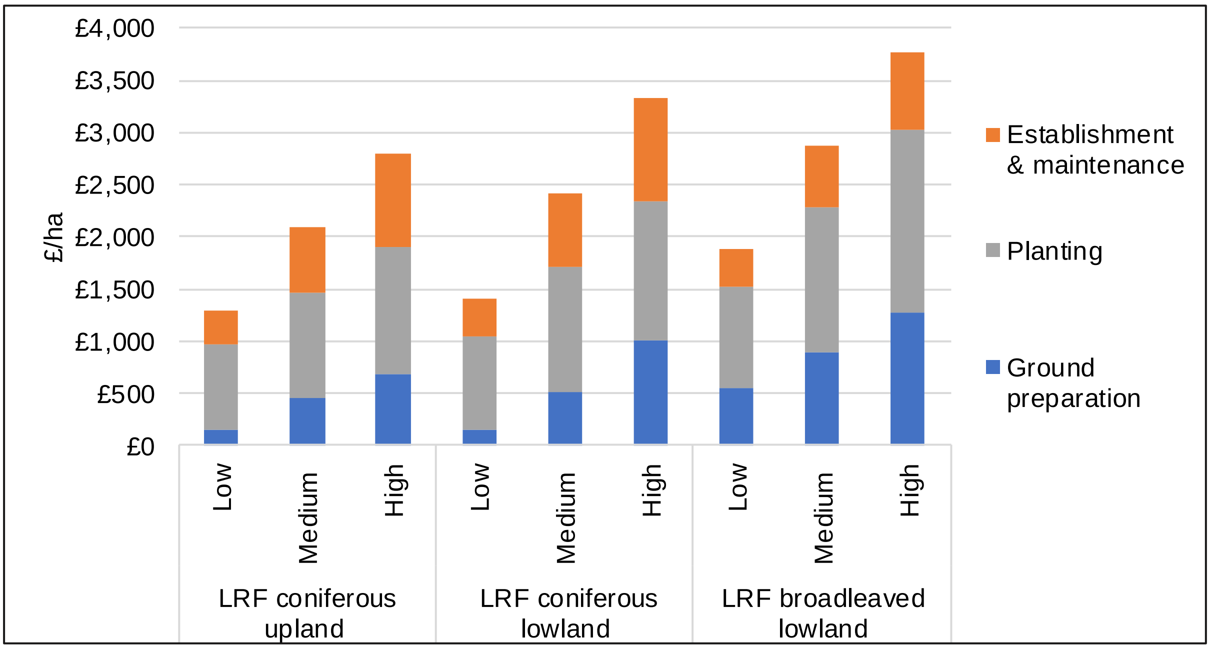
Consequently, a set of three scenarios for conventional long rotation forestry were defined: lowland coniferous; upland coniferous; and broadleaved woodland (Table 3-2). Most broadleaved woodlands are created at wide spacing and maintained for amenity and biodiversity purposes, but a small proportion may be established at higher density and managed more intensively for quality broadleaves on better sites. It is this latter system which has been modelled, and the approach taken was to mirror as far as possible the coniferous LFR approach, i.e. minimising establishment costs whilst promoting volume production and higher value timber (log) content where site and thinning returns permit. While this system is not the current norm for broadleaved forests in UK, if broadleaved forest were in the future to be developed for both fuel feedstock and timber value, rather than just for biodiversity or amenity value, it is likely that this would be the approach taken. It is therefore useful to look at the costs of such a system

Table 3-2: Production scenarios modelled for LRF

Case	Description
Coniferous LRF in the lowlands	The typical case is medium to large scale productive coniferous forestry in lowland Great Britain, operated on a commercial basis (excluding any extra recreation or amenity provision costs). New planting will tend towards the lower cost outcome, with restocking tending towards the medium and higher cost outcome, but this will not always be the case. The scenario assumes UK Forestry Standard (UKFS) (Forestry Commission, 2017) compliance including a minimum of 10% open space, 10% other species and 5% native broadleaves.
Coniferous LRF in the uplands	The typical case description is as for coniferous LRF in the lowlands scenario, though applied to an upland site. However, the assumptions behind the costing for individual process steps are different, such as a reduced requirement for deer fencing, increased requirement for draining, different soil preparation techniques, and lower costs for labour and beating up as a result of cooler conditions and less vigorous vegetation.
Broadleaved LRF	The typical case is medium to large scale productive broadleaved forestry, predominantly in lowland Great Britain, operated on a commercial basis (excluding any extra recreation or amenity provision costs). Silver birch - and downy birch in cooler, wetter locations - is the primary species in this scenario, although alternative species including sycamore, beech and oak could be suitable. The planting densities assumed are significantly higher than those currently used for the majority of broadleaved forest planting in the UK for which maximum timber production is not the primary aim. New planting will tend towards the lower cost outcome, with restocking tending towards the medium and higher cost outcome, but this will not always be the case. The LRF Broadleaved scenario assumes compliance with UK Forestry Standard (Forestry Commission, 2017) which proposes a minimum of 10% open space, 10% other species and 5% native Broadleaved.

For each of these scenarios, judgments were made of the most likely requirements and characteristics of each process step and then costed up accordingly. A full description is given in (Ricardo, 2020) and costs for each step are summarised in Appendix 1. A comparison of costs for the establishment phase for each scenario, is given in Figure 3-3, which shows that in all cases the main cost in the establishment phase is for planting.

Figure 3-3: Range of establishment costs for conventional LRF



Converting these establishment costs to a cost per tonne of timber harvested for bioenergy is difficult. The yield per hectare may vary considerably by site, but more importantly there is the consideration that only a proportion of the crop will usually be used for energy feedstock. Moreover, the component not used for energy is the part which is of higher value, and which drives production. A consequence of this is that an innovation which produces a crop that increases the proportion of quality stemwood (i.e. sawlog) to residues, for example by reducing the amount of side branches, may produce less bioenergy feedstock per hectare, but may effectively reduce the cost per unit of energy owing to the greater amount of more valuable product. By increasing the value of the crop, it may also increase its attractiveness as a commercial proposition, hence driving additional planting and increasing the overall amount of feedstock produced.

3.2 Short rotation forestry

3.2.1 Production

Short rotation forestry is the cultivation of fast-growing species at planting densities that allow significant biomass yield to be obtained over a timescale of ten to twenty-five years, rather than the forty to one hundred years for more conventional forestry.

Most of the process steps associated with short rotation forestry are broadly similar to those for conventional LRF (Section 3.1.1), with the same preparation of site and planting material, establishment and crop management. Key differences are in thinning and harvesting:

- Owing to the time scales involved, thinning is less likely (although one potential innovation is to combine higher initial planting density with a mid-rotation thinning).
- Harvesting is a less machinery intensive activity than in LRF owing to the smaller stem size of the harvested material.

If the main objective is bioenergy production, species selection is more likely to focus on broadleaved species than on coniferous species because the wood density of broadleaved species tends to be greater.

The harvested material can be cut to length, stacked by roadside and air dried, or chipped on site.

At the end of the rotation there are various options for the site. The stumps can be removed or ploughed in ready for a completely new planting on a clean site. Alternatively, the cut stumps can be allowed to regrow new coppice stems, which can then be either allowed to continue to grow as conventional multi-stemmed coppice or thinned to the best single stem to regrow a single stem tree on the original stump.

The shortening of the rotation reduces the potential for the co-production of sawlogs and the resultant long lived harvested wood products such as lumber, with the associated long-term sequestration of carbon. However, there may still be the potential for some timber to be used for products such as fence posts and panel boards, if required.

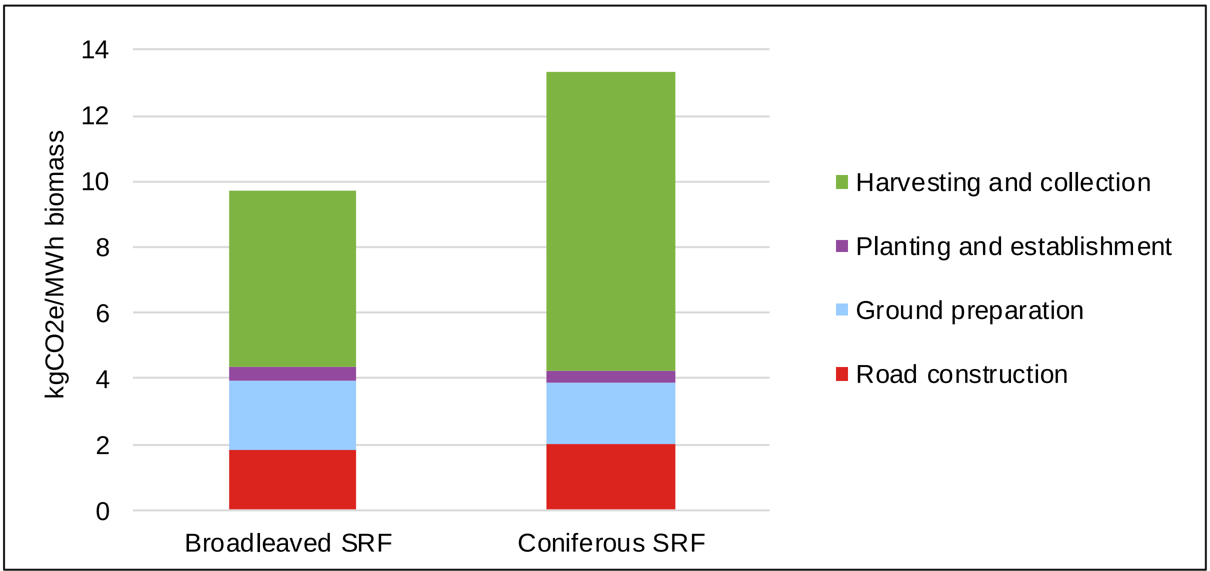
3.2.2 Greenhouse gas emissions from SRF

GHG emissions from 'typical' production of broadleaved and coniferous SRF from ground preparation, through to harvest and collection are shown in Figure 3-4. Emissions from soil organic carbon, are excluded but are discussed further below.

Emissions from production are estimated to be 9.7 kg CO_2e/MWh (2.7 kg CO_2e/GJ) of biomass feedstock for broadleaved SRF and 13.3 kg CO_2e/MWh (3.7 kg CO_2e/GJ)) for coniferous SRF. A further breakdown of emissions by source is given in Figure 3-5. Sites are assumed to have fencing for protection from pests while establishment takes place, herbicide is applied during planting and establishment phase, and urea is applied as a stump treatment at harvesting. No fertilisers are assumed to be applied.

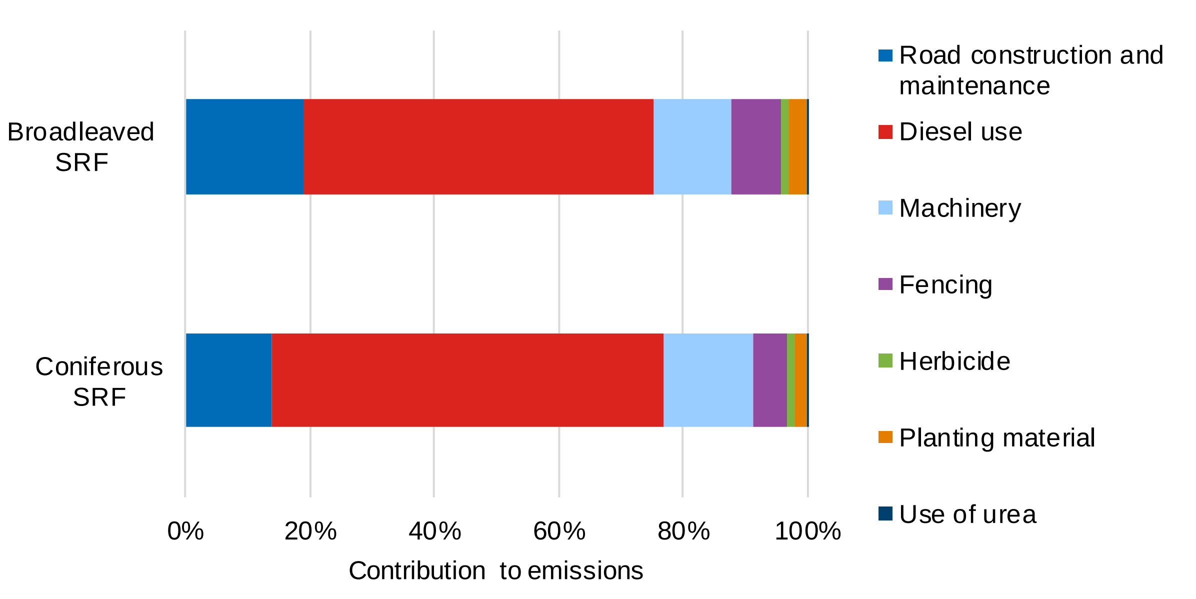
For both broadleaved and coniferous SRF, emissions arise principally in the harvesting and collection step, and arise mainly from diesel use, although emissions associated with road construction and ground preparation are also significant. Diesel use is the dominant source of emissions accounting for about 60% of the overall emissions; around 80% of this occurs during harvesting and collection. Road construction and maintenance accounts for about 1.8 kg CO_2e/MWh, and production emissions would be reduced if there was existing access and additional road construction was not needed.

Figure 3-4: GHG emissions by process step from production of wood for bioenergy in SRF



Source: derived from (North Energy, Forest Research and NNFCC, 2018). Includes emissions up to forest road only; emissions from transport and processing away from the forest are excluded

Figure 3-5: Sources of GHG emissions in production of wood for bioenergy in LRF



Source: derived from (North Energy, Forest Research and NNFCC, 2018). Includes emissions up to forest road only; emissions from transport and processing away from the forest are excluded

Estimated emissions from changes in soil organic carbon due to the cultivation of ex-agricultural soils for the creation of SRF are shown in Table 3-3, and as for energy crops are based on data from . Again as for energy crops there is a large variation in values, and empirical studies show that it is generally the soil carbon stock of the land prior to planting which is important in determining the change in soil carbon stock (Rowe, et al., 2016) (Whitaker, et al., 2018). Soils with high carbon stock prior to planting of energy crops are at greatest risk of soil carbon loss, and soils with a low carbon stock prior to planting are more likely to see an increase in soil carbon.

The table shows that planting of SRF on land previously used for rotational crops will generally lead to an increase in soil organic carbon, and that in these cases, this will offset the emissions associated with production by a large margin, leading to an overall negative GHG flux. Note that the negative emissions shown for coniferous SRF on a per MWh basis have a greater magnitude due to the lower yield assumed for coniferous SRF.

If SRF were to be grown on permanent grasslands, then the data suggests that on average, there would be a net soil emission, which in the case of broadleaved SRF is similar to emissions from the production stage. Due to the lower assumed yield for coniferous SRF, emissions from changes in soil organic carbon if planted on land previously in permanent grassland, could be greater than those from production. However, even where this is the case, total emissions (i.e. including those caused by the land use change) from production of the feedstock would still be only about 20 kg CO_2e/MWh for broadleaved SRF and 34 kg CO_2e/MWh for coniferous SRF (based on mean values for GHG flux from land use change). Thus, SRF biomass for energy production would still deliver substantial GHG savings compared to use of fossil fuel alternatives.

In all cases, growing SRF on land which was previously in use for conventional forestry would lead to a net loss in soil organic carbon.

Table 3-3: GHG flux from change in soil organic carbon due to direct land use change to SRF

Original land use	Annualised change in soil organic carbon		
	Mean	Low	High
	t CO_2e per ha per year		
Rotational crops	-2.94	-5.87	-0.28
Permanent grassland	0.69	-0.86	4.20
Forest	1.83	0.13	6.26
	kg CO_2e/MWh biomass feedstock[a]		
	Broadleaved SRF		
Rotational crops	-45.2	-90.2	-4.3
Permanent grassland	10.7	-13.3	64.6
Forest	28.1	2.0	96.2
	Coniferous SRF		
Rotational crops	-88.0	-175.6	-8.5
Permanent grassland	20.8	-25.8	125.7
Forest	54.7	3.9	187.3

[a] Changes per ha have been converted to a per MWh basis assuming a 15 year rotation period and annualised yields of 12.3 odt/ha per year for broadleaved SRF and 6.3 odt/ha per year for coniferous SRF[5].

Source: derived from (Richards, et al., 2017)

3.2.3 Costs of short rotation forestry

The typical production scenarios defined to allow analysis of the costs of producing wood from SRF are described in Table 3-4. For each of these scenarios, judgments were made of the most likely requirements and characteristics of each process step and then costed up accordingly. As for conventional LRF, since a number of factors can influence costs, low and high costs are estimated alongside typical costs. These do not represent minimum and maximum costs, but the likely ranges. A full description is given in (Ricardo, 2020) and costs for each step are summarised in Appendix 1.

As for energy crops (Section 2.4) the estimated production costs were used in a discounted cash flow model to calculate the overall costs of production per unit of biomass produced; the results are shown in Table 3-5 on both an undiscounted and discounted basis. For the discounted values, (at 5% and 10%) the cost is a levelized cost of production and represents the price the landowner would need to receive to achieve an internal rate of return equal to the discount rate. While costs of production are higher for broadleaved SRF on a per ha basis, the higher yield obtained means that costs per oven dried tonne (odt) or GJ are lower. With a 5% discount rate, the typical production cost for chipped wood at the forest roadside is estimated to be £$_{2019}$ 178/odt (£$_{2019}$9.3/GJ) for coniferous SRF and £130/odt ((£$_{2019}$ 6.8/GJ) for broadleaved SRF, which has a higher annualised yield. At 10% these costs rise to £$_{2019}$ 247/odt (£$_{2019}$ 13/GJ) and £$_{2019}$ 181/odt (£$_{2019}$ 9.5/GJ) for coniferous and broadleaved SRF respectively.

These costs exclude land rent, because it is a variable which would not be affected by technical innovations. However, it is useful to understand the effect that land rent has on the price of the biomass produced, as the production cost will affect the price that the farmer would need to receive for the biomass in order to make its production profitable. If SRF were to be grown on lower grade agricultural land, then land rent might be payable. The impact of including this is shown in Figure 3-6 where the medium case assumes the low land rent assumed in the energy crops analysis of £131/ha, and the

[5] These are typical yields and there could be substantial variation e.g. based on the range of values seem in trials to date broadleaved SRF could vary between 5 and 27 odt/ha per year, and coniferous SRF between 4 and 8 odt/ha/ per year.

high case the average land rent of £181/ha. This reflects the fact that SRF is unlikely to be grown on high quality agriculture land. The impact is significant, adding over 20% to the cost of the wood chip produced.

Figure 3-7 shows the contribution of different steps to the total levelized cost of production (at a discount rate of 5%. As for energy crops, harvesting is the most significant element of production costs; within this clear felling accounts for about 60% of the costs and chipping 40%.

Table 3-4: Production scenarios modelled for SRF

Case	Description
Coniferous SRF	Fast growing coniferous species (e.g. Sitka spruce or Douglas fir) on medium quality land, grown without thinning on a 15 to 20-year rotation and harvested conventionally as pole length or shortwood. The lower cost outcome assumes new planting, whereas the medium and higher cost outcomes assume restocking in forest conditions. The spacing adopted for the three cost outcomes (2,700, 2,700 and 3,100 stems ha^{-1}) is towards the lower end of SRF options to avoid exacerbating establishment costs and to maximise tree size at felling (even at the potential cost of some total volume); this has a major effect on harvesting costs. Figures are tentative, especially for growth rates, tree size and harvesting costs. The scenario assumes UKFS compliance including Section 6.1 Guideline 10 for a minimum of 10% open space, 10% other species and 5% native Broadleaved. However, these amendable (increased and reduced) costs are assumed to lie within the overall envelope of costs assumed.
Broadleaved SRF	Fast growing native Broadleaved on medium quality land in the lowlands, grown without thinning on a 15- to 20-year rotation and harvested conventionally as pole length or shortwood. For the typical scenario, we have selected native species because there is not yet widespread acceptance of non-native species, though several non-natives have significant potential for bioenergy production. The costs include initial establishment, so a reduction in planting cost for subsequent rotations may be feasible if coppice regrowth is used, followed, if necessary, by 'singling', where all but one of the re-growing stems are cut leaving just one to mature. The lower cost outcome uses fast growing poplar on farmland, whereas the medium and higher cost outcomes use birch in forest conditions. The spacing adopted (2,500, 2,500 and 3,100 stems ha^{-1}) is towards the lower end of SRF options to avoid exacerbating establishment costs and to maximise tree size at felling (even at the potential cost of some total volume), which has a major effect on harvesting costs. Figures are tentative, especially for growth rates, tree size and harvesting costs. The scenario assumes UKFS compliance including Section 6.1 Guideline 10 for a minimum of 10% open space, 10% other species and 5% native Broadleaved.

Table 3-5: Modelled cost of chipped wood from SRC at forest roadside (£2019)

Parameter	SRF type	Units	Case	Un-discounted	5% discount rate	10% discount rate
Total cost per hectare	Coniferous	£2019/ha	Low	7,632	4,167	2,594
			Typical	11,785	6,568	4,196
			High	16,645	9,470	6,203
	Broadleaved		Low	8,560	5,009	3,391
			Typical	12,440	7,127	4,716
			High	17,724	10,398	7,061
Total production	Coniferous	odt/ha	All cases	80	37	17
	Broadleaved			120	55	26
Production costs per odt	Coniferous	£2019/odt	Low	95	113	153
			Typical	147	178	247
			High	208	256	365
	Broadleaved		Low	71	91	130
			Typical	104	130	181
			High	148	189	272
Production costs per GJ	Coniferous	£2019/GJ	Low	5.0	5.9	8.0
			Typical	7.8	9.3	13.0
			High	11.0	13.5	19.2
	Broadleaved		Low	3.8	4.8	6.9
			Typical	5.5	6.8	9.5
			High	7.8	10.0	14.3

Figure 3-6: Impact of land rent on SRF production costs (at 5% discount rate)

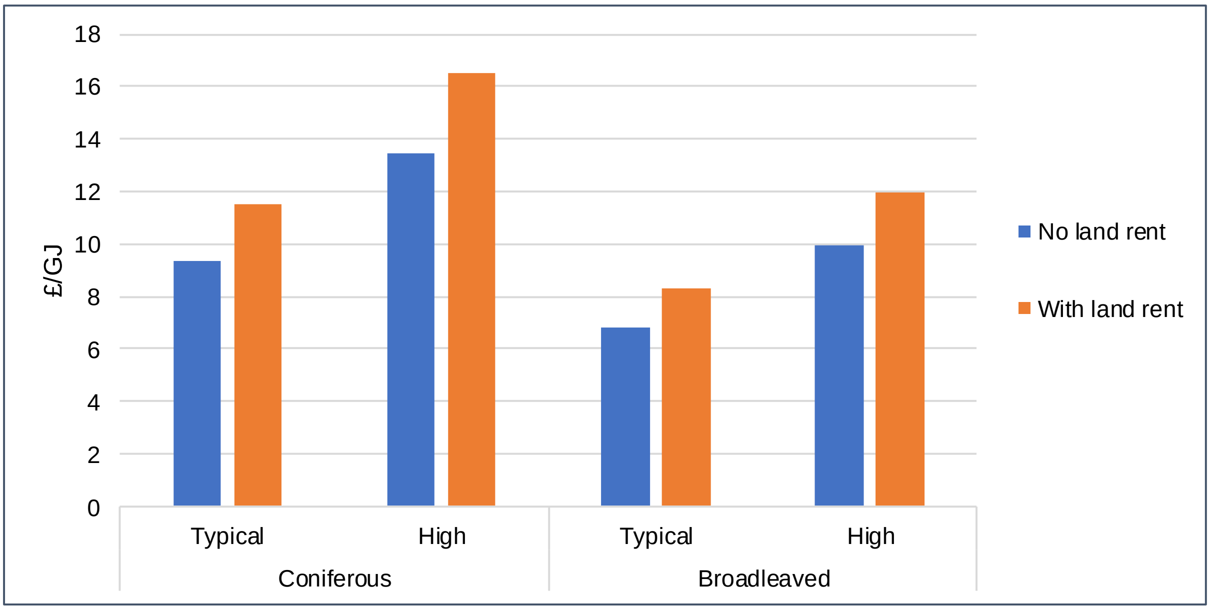
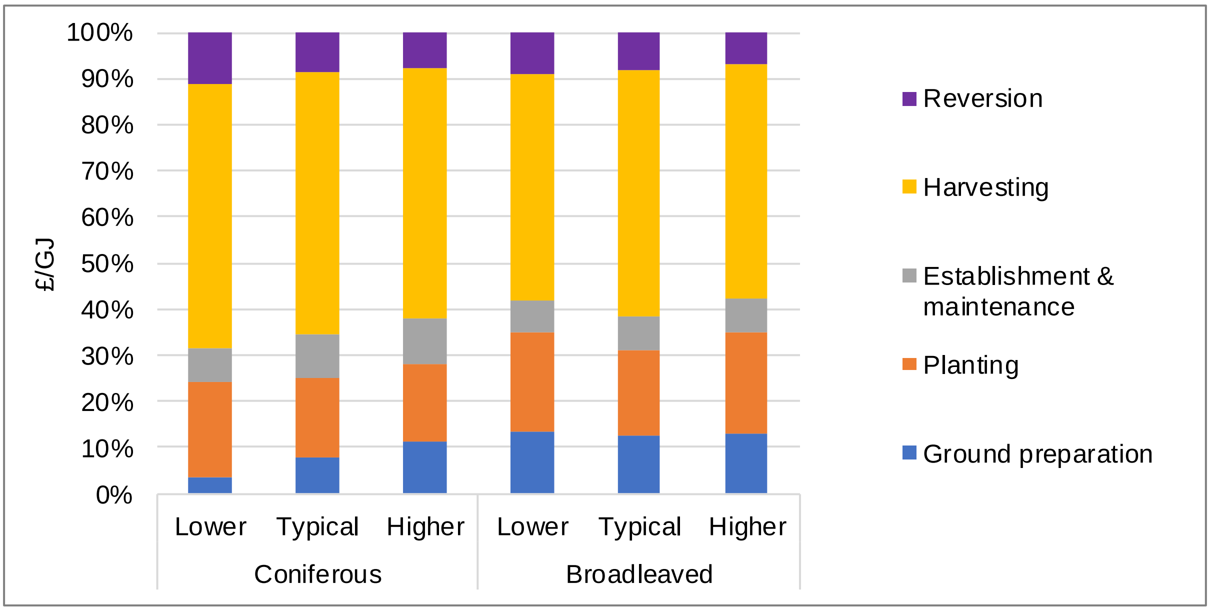


Figure 3-7: Contribution of process steps to levelized cost of SRF production (for discount rate of 5%)



3.3 Innovation areas for forestry

This section gives an overview of the innovations identified on the basis of the literature review and expert knowledge within Forest Research. A more detailed description of each of the innovations, which also includes an assessment of the additional environmental benefits some of them may deliver, and of any potential barriers to successful implementation of the innovations can be found in the accompanying report (Ricardo, 2020).

3.3.1 Planting stock preparation

Species selection for a given site will be driven by many considerations. However once a species has been selected, there are two major factors which could enhance the outturn of the area: provenance selection and genetic selection. Provenance selection uses the natural diversity and acclimation of a species to specific regional conditions. It may use plants raised from seed from already acclimated species (i.e. a local seed source) or seed stock from elsewhere primarily to improve growth in the expected conditions (Whittet, et al., 2019). Genetic selection uses the selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors.

Four specific innovations related to planting stock preparation (species selection, provenance selection, genetic selection and species mixture) were identified and are discussed further below.

3.3.1.1 Species selection

3.3.1.1.1 Description

Commercial LRF has focussed on a relatively narrow range of species chosen primarily for their rapid volume growth and good stem form for sawlog production but implicitly also for their survival. However, today's challenges raise additional considerations such as the amount of biomass that could be available for bioenergy (and carbon stocks), GHG emissions and other environmental impacts which may favour different species or suggest alternative species in different situations (Jansson, et al., 2017).

Broadleaved forests have a slightly broader range of common species than commercial coniferous forests [(Kerr, 2011), (Kerr & Evans, 2011), (Cope, et al., 2008), (Hubert & Cundall, 2006)]. Owners of broadleaved woodlands tend to have a wider range of objectives, therefore species choice may be the result of species appearance and biodiversity value as well as the criteria underpinning the selection of coniferous species.

Species must be considered individually. Characteristics that hold at genus level, e.g. all species of the larch (*Larix*) genus are deciduous whereas all species of the eucalyptus genus are evergreen, do not necessarily indicate utility for bioenergy supply such as rapid volume growth or high wood density. Species choice has therefore to be done at an individual species level based as far as possible on experience of their performance in the UK and then overlaying additional information specific to bioenergy production as soon as it becomes available.

Kerr and Jinks (2015) reviewed potential new species for the UK, and it is feasible that this initial list could be used to inform species choice for bioenergy supply. Factors which will be important in this choice are: susceptibility to known pests and diseases; volume growth; wood density/calorific value; and availability of planting stock.

(Willoughby, et al., 2007) summarises the establishment and early growth of 44 native and non-native species on a variety of different site types in lowland Britain. A general conclusion was that all of the species tested, apart from tulip tree and walnut, gave acceptable survival and growth, indicating a wide choice of possible future alternatives in lowland Britain. In the case of non-native species, such as Eucalyptus and Nothofagus, factors such as resistance to periods of cold weather have been shown to be important (Leslie, et al., 2014), (Kerr, 2011), (Stokes, 2014). Two new series of trials established in 2009 covering Scotland, England and Wales, which compare 42 species, including 116 provenances across 5 sites, will add to this growing body of information about a wider range of species (Reynolds, Submitted).

Volume growth of individual species is strongly influenced by the site conditions. The cKerurrent series of English SRF trials (12 species on 4 ex-agricultural sites) show marked species differences from site to site but also statistically significant interactions between species and site (McKay, et al., In preparation). This is consistent with the findings of (Willoughby, et al., 2007).

In the context of this feasibility study it is important to note that wood density and calorific value have not been key species selection criteria for any of the forest groups. Consequently, there is considerable scope to widen the range of species to include those that have greater yields of biomass, but which ideally are established in a similar way to familiar species. *Eucalyptus glaucescens*, sweet chestnut (*Castanea sativa*) and sycamore (*Acer pseudoplatanus*) may be worth further consideration because these species have proven adaptation to the UK environmental conditions plus good growth rates and in addition the wood has a higher density than common coniferous species and other fast growing broadleaved species such as poplar and willow.

Availability of good quality seed (or stock plants if the species is raised from cuttings) and ease of nursery production are important.

Individual species may have particular characteristics that are seen as benefits (e.g. sweet chestnut and Japanese cedar coppice well; *E. glaucescens* is said to be less attractive to deer; London plane is tolerant of air pollution) or disadvantages (e.g. sycamore is prone to squirrel damage; black locust has been invasive in some countries). Impacts on native flora and fauna (Quine & Humphrey, 2010), (Peterken, 2001) may also be important considerations in some situations.

Tree species selection applies to the start of the bioenergy supply chain. If new species are to be introduced, this could take several years as seed will need to be sourced and, if necessary, treated to break dormancy and ensure high germination, before it can be used for planting. Usually seedlings are raised in specialist nurseries. Planting material is grown to match the expected site conditions and may take one to three years, so nursery owners would need to be persuaded that the market will materialise and also that the market will bear the cost for less common species. Quality Assurance procedures will be needed to ensure that poor quality seed is not marketed by unscrupulous individuals. Some species can be raised from sowing seed directly (see later), which avoids the nursery phase; nevertheless, seed has to be sourced and possibly treated to break dormancy.

3.3.1.1.2 Status of innovation

TRL is 5-9 for several species as a number of alternative species for 'long' and 'short' rotation forestry are being trialled currently by Forest Research as part of core-funded work, in conjunction with Forestry England and Forestry and Land Scotland and private sector organisations (e.g. Future Trees Trust). (Willoughby, et al., 2007), (Kerr & Jinks, 2015), (McKay, 2011), and (McKay, et al., In preparation) summarise a range of recent experiments and trials.

3.3.1.1.3 Potential impacts

Yield may be increased by up to 50% if the species combines fast growth and high density and/or calorific value . More typical increases may be 10-20% (Willoughby, et al., 2007).

The exact impact on yield is difficult to gauge, as the volume yield may increase or decrease relative to the original species choice, but the increase in wood density and therefore biomass, could compensate for any volume losses.

Costs. The main difference in cost is likely to come from the increased cost of planting material (usually seedlings) and potentially increased protection costs (fencing/tree shelters), depending on the species. Plant costs may be increased significantly if the plant demand is too great to be met from British seed sources and seed has to be imported. Even if seed can be sourced from within Britain, the initial scale of production is likely to be modest until the market can respond so costs will initially be higher compared to the present large-scale commercial operations. Steps to ensure the origin, identity, health status and viability of seed will add to the cost (Lee & Watt, 2012). Other costs are likely to be similar.

GHG emissions per unit of biomass produced are likely to be reduced as emissions from planting will not increase, but as yield is increased, emissions per tonne harvested will fall.

3.3.1.2 Provenance choice

3.3.1.2.1 Description

The natural distribution of most tree species covers a range of situations, e.g. in latitude, altitude, and distance from the sea. Over generations natural selection has resulted in the adaptation of the trees in a particular area of the natural range to their local conditions. When plants from a given original seed source (provenance) are grown in a different location, the growth may be better or worse. In the UK it is generally the case that volume growth can be increased by choosing an original seed origin that is further south than the intended planting site because the trees will begin growth earlier in the spring and become dormant later in the autumn than the local provenance.

Trials of different provenance have been undertaken to investigate growth rate and characteristics (Hubert & Cundall, 2006), survival in the British climate [(Kerr, et al., 2015), (Lee, et al., 2015), (Kerr, et al., 2016)], resistance to pests and pathogens (Field, et al., 2019), as well as adaptation to future effects of climate change [(Whittet, et al., 2019), (Barsoum, 2015)].

3.3.1.2.2 Status of innovation

The principle is well established for both coniferous and broadleaved species but the TRL status varies from 9 to 5 depending on species. For the main UK commercial coniferous species Sitka spruce, Washington provenances are used for some areas in Wales rather than the Queen Charlotte Island provenance used elsewhere in the UK so the TRL is 9. For other species such as Pacific silver fir, there are replicated field experiments but not uptake by the sector and TRL is 5. For other species that would be novel in the UK, e.g. acacia, TRL is closer to 2. Hubert and Cundall (Hubert & Cundall, 2006) provide advice on provenance choice for a range of broadleaved species including oak (*Quercus robur* and *Q petraea),* ash, birch, sycamore, cherry, beech, and aspen.

3.3.1.2.3 Potential impacts

Yield. The general principle has been demonstrated with Sitka spruce (Samuel, et al., 2007) and more recently by Lopez and McLean [unpublished data] as well as silver birch for which Lee (Lee, 2017) found that an increase of 20% in yield could be obtained in provenances from 2-5 degrees further south. Kerr et al. (Kerr, et al., 2015) summarised the findings of European silver fir trials and concluded that a seed source from a small area of Calabria gave the best growth, with a volume index of $1.6m^3$ – $2.0m^3$, against a mean for all provenances of $0.9m^3$. Within this general principle however there are examples where there has been no significant difference between the studied provenances (e.g. Pacific silver fir (Kerr, et al., 2016)). A stakeholder commented that *Eucalyptus gunnii* seed sourced from higher altitudes is likely to be better for frost tolerance.

Costs Plant costs are likely to increase if seed has to be imported. Even if seed can be sourced from within Britain, the scale of production is likely to be modest so costs will increase compared to the present commercial scale operations. Steps to ensure the origin, identity, health status and viability of seed will add to the cost (Lee & Watt, 2012). Other costs are likely to be similar.

3.3.1.3 Genetic improvement

3.3.1.3.1 Description

Gene modification is not practiced in the UK therefore genetic improvement is achieved through selection and breeding by means of a series of steps. At its simplest the first is to identify individuals of superior phenotype growing in situations typical of the intended site, i.e. individuals that have desirable traits - in this case volume growth, density and/or calorific value. These individuals (referred to as 'plus trees') can be used as sources of seed or cuttings. The next significant improvement is achieved by setting up seed orchards of superior trees so that the random fertilisation of female flowers by pollen released by other trees in the seed orchard creates genetically improved seed. More advanced selection and breeding can be implemented by deliberately crossing a superior mother and father and selecting the best of their offspring to multiply up for commercial deployment. Because of the relatively short time scale in which the innovation is hoped to deliver on its potential, genetic improvement of most of the suitable species can be achieved only by simple phenotypic selection. Nevertheless, more advanced selection, testing and controlled crossing of superior individuals is feasible for a few species even allowing for the limited timescale and in the present context is more suited to SRF than LRF owing to the shorter rotation lengths in SRF.

Genetic improvement of a tree species would take place in advance of the stock introduction at the start of the supply chain for the bioenergy.

3.3.1.3.2 Status of innovation

For the most promising bioenergy species, TRL is 1-7 depending on species. Some of the species that have recently demonstrated significant potential for bioenergy production in a wide range of UK environmental conditions have not been part of a selection and breeding programme. Examples include *Eucalyptus glaucescens*, chestnut (*Castanea sativa*), sycamore (*Acer pseudoplatanus*) and possibly red alder (*Alnus rubra)* and common alder (*A. glutinosa*. In addition, these species have the potential benefit of higher wood basic density, leading to higher energy density. These species have been established in trials by Forest Research in England, Wales and Scotland confirming their superiority compared to other alternatives, including Sitka spruce and Japanese larch after 5 - 8 years of growth. Existing selection and breeding programmes for commercial Conifers such as Sitka spruce are likely to continue to focus on timber production however increased timber production is likely to be linked to increased production of smaller dimension material that could be utilised for bioenergy.

3.3.1.3.3 Potential impacts

Yield Genetic improvement considerations for each of the species are described below.

- An attractive innovation for *E. glaucescens* is to introduce half-sib families from selected trees from a wide range of provenances to optimise adaptability to the UK conditions, productivity, variability and the possibility to continue improving over generations. Breeding programmes in

Eucalyptus sp. have proved to be very successful, multiplying by five the productivity over generations, i.e. in Brazil and China [(IBÁ, 2015) and (Xie, 2015), respectively]. Particularly for SRF, a trial could be established after two years, with assessments and selection after five years; in this way improved material could be available after seven years from the start of the program.

- Chestnut is a species with a long history of commercial use in the south of UK. A breeding program has made useful progress; selected genotypes are consistently superior to unimproved chestnut (Karen Russell personal com). This programme has had limited funding in recent years, but it still has the potential to optimise the breeding stock for different site conditions.
- Sycamore is another species very well adapted to UK conditions and some progress has been achieved by breeding. Candidate plus trees have been selected across the countries and established in clonal seed orchards. These orchards are reaching seed production and currently individual family trials investigating the genetic value for each parent are being evaluated. This will optimise the gains in adaptability and growth of the breeding populations in about five years after the new trials are established.

If SRF becomes more widespread, breeding specifically for biomass production could contribute substantially.

Costs Plant costs are generally greater for the first generation of genetically superior plants and they are substantially more for plants derived from controlled crosses.

3.3.1.4 Mixed species stands

3.3.1.4.1 Description

This innovation involves the increased use, when establishing new LRF, of bespoke ‘overyielding’ species mixtures chosen with a potential bioenergy market in mind (this contrasts with ad hoc mixtures in which the components are not selected for a production objective). This can be done to a range of degrees, from the use of nurse tree species to protect the crop, especially in exposed sites (Nord-Larsen & Meilby, 2016), to full mixtures of species, which has been shown to be able to increase yield significantly (Mason & Connolly, 2014) as well as offering landscape benefits (Grant, et al., 2012). Equivalent information is not available for SRF although in theory the same potential benefits of mixed species are possible.

3.3.1.4.2 Status of innovation

TRL is 5-9 depending on species. The use of mixed species stands are the subject of current research by Forest Research who are working with international scientists on the silviculture, growth and yield of mixed species stands.

3.3.1.4.3 Potential impacts

Yield Mason and Connolly (Mason & Connolly, 2014) report that stands of two species when mixed together can be up to 43% more productive than equivalent single species stands. This observation of ‘overyielding’ of species mixtures is well supported in the forest science literature but does not, of course, have universal applicability to any mix of different tree species.

Costs Although management throughout the process chain is slightly more complicated as noted during the stakeholder consultation, the evidence from Forest Research unpublished evaluations indicates that the impacts on costs are probably close to neutral. The possibility that management is more complex was also identified by a stakeholder who noted that mixed species stands look pleasing, but they are difficult to manage.

3.3.2 Land preparation

Various techniques exist for land preparation (Lof, et al., 2015), (Technical Development Branch, 2002), e.g. scarification, mounding, ripping, ploughing and also weeding. In the case of restocking, harvesting residues can be managed in a variety of ways that affect the next crop. While site characteristics may determine that some options are unsuitable, choice of preparation technique can influence initial establishment cost (in terms of both the initial ground preparation itself and further potential requirements for herbicide and pesticide), quality of establishment and hence initial growth rate. GHG emissions as a result of loss of soil carbon as a result of soil disturbance may also be affected. Soil preparation by ripping is a potential innovation

3.3.2.1 Description of soil preparation by ripping

Ripping is used to increase the available soil volume, aeration, soil water infiltration, drainage and root exploration (Ruiz, et al., 2008). Ripping fractures soil structure without mixing soil horizons and it is usually the first stage in a two-step site preparation process that also involves weed control or other soil preparation methods to control vegetation and create suitable microsites for tree growth (Gwaze, et al., 2007).

Ripping encourages deeper root development than the other soil preparation methods, and greatly improves water use. Ripping allows rapid root exploitation of different layers of soil, while also increasing infiltration of rain water. These conditions facilitate easy and rapid tree establishment.

3.3.2.2 Status of innovation

In the context of bio-energy production, the TRL is 6. The basic technique needs to be refined and evaluated for present day issues such as soil carbon, GHG emissions, and diffuse pollution as well as the impact on bioenergy production and costs. Target soils for short rotation forestry should be tested to quantify the effects.

3.3.2.3 Potential impacts

Yield The benefits in tree survival were quantified for oak and walnut which increased from 9% to 61% in oak and from 41% to 74% in walnut (Ashby, 1996). The same study also showed better growth following ripping with an increase in height from 2.2 m to 4.5 m in oak and from 2.6 m to 5.5 m in walnut, i.e. >100% gain. Another benefit is the homogeneity achieved by the stand after ripping preparation.

Costs Although the cost of cultivation may play a significant role in the choice of method, it should be borne in mind that if compaction is not dealt with prior to establishment it may result in a substantial reduction in the growth and health of the forestry crop. Ripping is, therefore, an effective, recommended practice for some sites and may be particularly beneficial on agricultural sites that have developed a plough pan.

3.3.3 Planting and establishment

Establishing and planting of material in forestry falls broadly into two categories: natural regeneration, where the crop itself provides the new seed material for subsequent cohorts, and planting of nursery grown material. The former system leads largely to continuous cover forestry (CCF), which provides a more diverse size and age structure than the more usual clear fell and replant system. Although CCF requires no or little effort for ground preparation to regenerate the stand, active management is required to prepare the 'parent seed' trees, which need to reach maturity and produce viable seeds. and to 'respace' the regeneration to provide a suitable crop balance (Davies & Kerr, 2015); (Mason, 2015).

Alternatively, a planting system can be used – this has the advantage of specific choice of species and provenance and a more traditional rotational management system, but with higher establishment costs. The spacing of commercial crops used over the past 50 years has been determined through experimentation to balance short-term initial costs of plants and establishment operations with productivity and product outturn in the longer term.

A single species or a mixture of species may be chosen for planting depending on the management objective. A variation on mixed species is to use one species as a ‘nurse’, e.g. to provide shelter, during the early growth phase to provide a better growing environment for the more desired final crop species. In time, the nurse species is usually shaded out by the desired crop species. An increased use of ‘nurse’ trees may provide an additional source of biomass in mixed forests (Nord-Larsen & Meilby, 2016). The addition of high-quality planting stock to undermanaged and understocked woodlands can help to boost the total biomass on site, a point which was also raised in the stakeholder consultation.

Seedlings planted for forestry usually originate from specialist forest nurseries, which makes it possible to specify the species or plant characteristics. Nursery production of seedlings are subject to ongoing innovations such as the use of light of specific quality and intensity (Hernandez Velasco & Mattsson, 2019), manipulation of the seedling type (Böhlenius & Övergaard, 2016) and improvement in cutting systems.

Innovations identified for this step include direct seeding (discussed in Section 3.3.3.1) and changing initial spacing between trees (discussed in Section 3.3.3.2). Enrichment planting of understocked woodlands was raised as a potential innovation but has been covered within Section 3.3.1.1 on species choice and is not discussed further separately.

3.3.3.1 Direct seeding

3.3.3.1.1 Description

Direct seeding is the process of sowing tree seeds by hand or machine, directly onto a prepared field/forest site. Current planting practice for forestry generally involves raising seedlings or cuttings in a nursery; the planting stock and subsequently planting at the field site are both expensive. Direct seedling offers an alternative approach which may be more attractive to farmers.

3.3.3.1.2 Status of innovation

The application of direct seeding for bioenergy production is a new concept which on the basis of expert opinion has potential in terms of economic viability while also producing a varied and visually attractive woodland that may be more appealing to some landowners and the public. The basic technique needs to be evaluated for bioenergy production and economics in likely areas of uptake in order to develop guidance. *TRL* is 7 for both broadleaved species on lowland sites and coniferous species in upland sites.

3.3.3.1.3 Potential impacts

Yield: Trials so far have covered only the early growth phase so there is no robust information on final crop yield. Because of the varied species composition and size of the produce, direct seeding could be more suited to bioenergy markets than timber markets.

Costs: Bare seeds are highly susceptible to predation by a range of fauna, in particular mice, birds and voles (Parratt & Jinks, 2013). In nature each tree tends to produce extremely high numbers of seeds each year, with an extremely low level of survival rate. Typical figures are of the order of millions of seeds per hectare, which is uneconomical for direct seeding. Innovations to promote increased survival of seeds can make this a practical option in certain circumstances. (Willoughby, et al., 2004). By manipulating the proportion of expensive versus cheaper seed, the total costs of establishment by direct seeding can be brought in line with those of planting seedlings. A stakeholder commented that direct seeding may help to circumvent some of the additional management effort and costs of planting (from maintenance, strimming and spraying), and may be more cost effective because of the greater number of stems per hectare.

3.3.3.2 Changing initial spacing between trees

3.3.3.2.1 Description

The current standard spacing between trees for commercial coniferous planting is around 2 metres (Lawrence, 2013). This spacing was chosen as a reasonable compromise between the higher costs associated with planting material (more seedlings are needed at closer spacing) and the effect on the timber properties of the resulting trees, such as the increased size of branches and knots in trees grown at wider spacing. However, if sustainable production of bioenergy is a stronger consideration, closer spacing could become more favourable, as closer spacing (up to a point) will result in more biomass per hectare, particularly on shorter rotations which could provide supplies of bioenergy more quickly. Closer spacing could also potentially improve timber quality of wood material in a stand of trees that was not selected for bioenergy use. Conversely, if the requirement is for a target tree size to be achieved as quickly as possible (for example under SRF management), then a balance could be sought between spacing that encourages initial individual tree growth against loss of total volume.

3.3.3.2.2 Status of innovation

TRL It is difficult to judge the TRL exactly. On one hand, there are many historical examples of spacing trials that could be considered. On the other, the innovation could include a decision support process for quantifying the trade-offs involved in what spacing would be the best solution for a given situation. On this basis a TRL of around 6 or 7 would appear appropriate.

3.3.3.2.3 Potential impacts

Yield The potential impact on yield can be very roughly illustrated using Forestry Commission Yield Models. For example, models for Sitka spruce of the same volume productivity or “yield class” (14 m^3 ha^{-1} yr^{-1}) both with no thinning operations but different initial spacing of 2.4 metres or 1.7 metres can be compared. If the comparison is carried out at a stand age of 55 years (i.e. close to the age at which the trees would be felled in order to maximise long-term volume production) then the standing volume for the stand planted at 2.4 metres is 670 m^3 ha^{-1} and the standing volume when planted at 1.7 metres is 689 m^3 ha^{-1}, i.e. around 2.75% more volume. However, the average tree size is 0.74 m^3 and 0.49 m^3 respectively, i.e. the individual trees in the closer spaced stand are around 33% smaller.

Costs Planting at closer spacing will cost more both in terms of planting material and potentially operations such as thinning. This would need to be balanced against any increase in the amount and nature of woody material produced.

3.3.4 Cultivation and maintenance

Although currently seldom used in UK forestry, fertilizer can help to improve establishment and initial growth rate. Digestate from anaerobic digestion (AD) plants is a high nitrogen, potentially low-cost fertilizer that can be used. Ash from combustion of wood, which is low in nitrogen but high in minerals, also has potential as a fertiliser. Use of organic fertiliser applications is discussed further in Section 3.3.4.1.

The monitoring of forestry crops, especially in remote and inaccessible sites, can be difficult and time and labour consuming. This can be particularly of concern when there is the risk of pests or pathogens, such as during an outbreak of *Phytopthera ramorum* in larch, when careful monitoring of crops is vital to identify outbreaks as soon as possible. The used of unmanned airborne vehicles (UAVs or “drones”) can significantly reduce the cost and increase the coverage of crop monitoring, and this potential innovation is discussed further in Section 3.3.4.2.

3.3.4.1 Fertilising crops using digestate or wood ash

3.3.4.1.1 Description

Digestate from AD is a potentially low-cost, nitrogen-rich organic fertiliser resulting from the recycling of animal wastes and food waste, which could be applied to boost biomass production. Application is most likely within lowland fast-growing silviculture – that is broadleaved or coniferous SRF – within an agricultural rather than forest land setting due to proximity to sources of digestate and access for digestate spreading. Success of this innovation would both be dependent on sensitive specification and close control in practice.

Using digestate as an organic fertiliser would most likely apply to the ground preparation stage, although top dressing during the establishment or pole stage might be conceivable. Use of digestate for fertilisation will affect establishment operations, especially weeding, and might also shorten rotation length.

Digestate provides nitrogen and carbon, as well as some minerals. Another option that has the potential to replace minerals (phosphorus, potassium, calcium and sodium, amongst others) is wood ash. Work in the UK (Pitman, 2006) and in other countries, particularly Europe, suggest that wood ash can be a potentially valuable, and low cost, additive to woodland sites to replace minerals. In some countries, such as Sweden and Finland, work has been done on granulating bottom ash (Korpilahti, et al., 1999) for convenience of distribution, preventing it blowing away, and slowing the release of minerals (Nieminen, et al., 2005). Trials are required to clarify the site characteristics and circumstances where increases in yield justify the cost of application and environmental risks are acceptable

3.3.4.1.2 Status of innovation

TRL is difficult to gauge and could range from one (because the innovation has not been investigated for forest crops) to six (because it has been proven within the agricultural context). The use of wood ash in forestry, and particularly granulated wood ash, has not been practiced in the UK, but has been investigated in other countries. Factors that would require investigation include application regimes and protocols, the form (concentration for AD; granulated or not for ash), and environmental impacts in forestry situations.

Whilst application of organic (and inorganic) fertilisers is common, and usually necessary, in agricultural production, but this is not the case within forestry. Firstly, there are no proven demonstrations of digestate application within forests and secondly the UK Forestry Standard tends to minimise fertiliser applications in general, limiting them to situations where they are necessary to achieve establishment or avoid the stagnation of plantations. Use of fertilisers, especially digestate from AD, could have a major impact on the ‘forest’ environment. A possible exception is the cultivation of trees as a biomass crop within an agronomic setting as ‘field’ crops rather than ‘woodlands’, for example a form of SRF.

3.3.4.1.3 Potential impacts

Yield. Digestate from AD supplies a rapid very significant boost to available nitrogen in a mobile form in the first year following application, which may significantly increase yield in tree crops in the short term, and in this respect might reduce rotations by one or two years, or enable harvesting of larger trees at the former rotation.

Costs. Although reduced unit cost might accrue from increased system productivity (such as tree size at harvesting), there would be increases in the cost of cultivation from the application and almost certainly in weeding. Excessive top growth, owing to a rapid boost in nitrogen availability, can also result in tree instability and root-collar snapping. The most likely beneficial specification would be a relatively modest application regime.

3.3.4.2 Remote sensing for crop monitoring and management

3.3.4.2.1 Description

A range of remote sensing techniques could be applied to assess growth rates and possibly bioenergy yield. Increasingly advances, including cost reductions, in satellite imagery, LiDAR and UAVs (drones) may provide a way of monitoring woodlands.

The innovation suggested is to investigate the application of promising remote sensing techniques to bioenergy production systems, e.g. the assessment of branchwood biomass, residue availability, and efficiency of site operations to optimise thinning, felling and extraction. Monitoring of crop performance, health and potential disease or pests and to provide up-to-date information to facilitate woodland management may also be valuable.

3.3.4.2.2 Status of innovation

TRL is 3 to 8 depending on the specific application. Universities tend to be the key players in sensor technologies as well as data handling and analysis of the very large data sets that can be generated. Some commercial companies (e.g. Treemetrics, Carbomap) have demonstration systems providing basic forest inventory and change detection. Forest Research are developing bespoke forestry applications.

3.3.4.3 Potential impacts

Yield. While remote sensing is unlikely to increase yields directly, there is likely to be indirect improvements through better forest health, and early treatment to reduction in growth and quality caused by pests and disease. The main benefits are likely to come through improved, more cost-effective management of the forest.

Costs Through improved understanding of woodland growth, structure and variability, remote sensing techniques have the potential to improve the overall efficiency of bioenergy production, especially for large-scale and/or remote locations.

3.3.5 Thinning

Optimum planting density is a balance between the cost of planting material and sufficient density to both ensure rapid canopy closure (and hence suppression of competitor plants), and to promote straight stems of good form to provide high quality sawlogs. However, as the crop matures, it is necessary to remove a proportion of the stock initially planted to allow more space for the growing trees. The first thinning, perhaps at between 15 and 25 years, may often be referred to as a “pre-commercial” thinning as the material removed tends not to include any commercial sawlogs, however it can contain a significant quantity of biomass. Thinning of overstocked woodland can also generate a significant quantity of biomass suitable for bioenergy end uses.

Earlier thinning of whole stems i.e. before year 15, was raised as a potential innovation by stakeholders and is discussed in the section on harvesting technologies. Thinning of overstocked woodlands was also suggested initially but as noted by one stakeholder thinning of overstocked woods presents a degree of risk and extra complexity, involving a style of labour that is inconvenient and costly, particularly in relation to current market prices. It is therefore not discussed further here.

3.3.6 Harvesting and collection

The terrain of many forestry sites has led to the development of specialist machinery for felling (harvesters which cut and de-limb trees on a one by one basis) and extracting trees (forwarders). Manual felling is a rarity in commercial UK forestry nowadays. There is currently development of revised harvester heads to deal with SRF/coppice material (Asikainen, et al., 2011); (Savoie, et al., 2013). In more remote areas, and with steeper terrain, heavy machinery may not be an option and cable extraction is necessary; on very steep slopes it may be necessary for chainsaw operators to fell the trees. Efficiency gains in harvesting and collection methods are possible with the advancement of modern technology (Davies & Kerr, 2015), particularly if there is an additional bioenergy market.

Potential innovations identified for harvesting are:

- Manipulating cut-off diameter (Section 3.3.6.1)
- Removal of stump to ground level (Section 3.3.6.2)
- Residue removal (Section 3.3.6.3)
- Stump and root removal (Section 3.3.6.4)
- Integrated harvesting system (Section 3.3.6.5)

3.3.6.1 Manipulating cut-off diameter

3.3.6.1.1 Description

The proposed innovation is to evaluate the impact of manipulating the choice of top diameter on combined biofuel and timber production systems. At harvesting, the stem diameter at which the uppermost cut is made can be manipulated which affects the amount of recovered roundwood produce and the tree tops left on site as potential biofuel. Whilst adjusting cut-off diameter to maximise value recovered is by no means novel, the potential for residue biomass gain or loss must be considered within roundwood harvesting systems (as opposed to some whole tree systems). This could be important in any novel system developed for biofuel utilisation.

In the first instance this innovation has impacts for thinning (if applicable) and harvesting and extraction, but it will also have impacts on steps earlier in the production process i.e. ground preparation and establishment operations.

3.3.6.1.2 Status of innovation

Manipulation of cut-off diameter within systems producing both a timber and a biomass crop has a TRL of 7.

Experience has shown that, irrespective of the selected ‘ideal’ diameter on any given site, it can be operationally difficult to achieve and in consequence the result may be a sub-optimal value recovery – usually meaning too much residue is left on site. However, where the value of fuelwood is greater than the small roundwood alternative use for the top end of the tree, a greater cut-off diameter will yield greater biofuel volumes for subsequent secondary extraction and this will have downstream operational consequences. Therefore, cut-off diameter is an important consideration in any novel harvesting system that may be proposed. Key players in developing this innovation would be management companies, private sector foresters, and managers of the national forest estates.

3.3.6.1.3 Potential impacts

Yield As an illustration of the potential brash yields, a trial on a typical upland clearfelled spruce site showed that the extracted residues increased from c. 100 green tonnes to c. 200 green tonnes when branches as small as 3 cm diameter were removed compared to when only larger (10 cm diameter) brash was removed. One commercial operation described by a stakeholder has developed a variant of this by harvesting a biomass product by running the stem from 14 cm diameter through harvester head until it snaps (i.e. de-branched to almost to the stem tip which increases volume yield by around 3 to 5%.

Cost Any benefit of *larger* cut-off diameter would result (depending on produce prices) primarily from the increased residue recovery value if it is then extracted. However, a *smaller* cut-off diameter can also increase value if the greater roundwood volume has greater value, or potentially if the lesser residue left on site hinders subsequent rotation operations *less*. A smaller diameter can also result in insufficient brash left on site for efficient harvesting on some sites.

GHG The GHG emission effects would appear to derive primarily from increased biomass recovery from sites and the markets supplied, but there may be marginal GHG effects owing to differences in machine hours involved in forestry operations.

3.3.6.2 Removal of stump to ground level

3.3.6.2.1 Description

During harvesting in commercial forestry, the lowest cut is made at the point where the stem starts to swell out. The stemwood above this cut is removed from the site but material below this cut (the stump) is usually left on site. Depending on the extent of swelling, the remaining stump can be up to 40 cm high and represents potential additional biomass.

Cutting stumps low has effectively always been good practice to maximise ‘log’ volume recovered and reduce restocking obstructions. The advent of large and increasingly sophisticated (expensive) harvesting and extraction machinery has reinforced this, owing to the operational impediment that ‘high stumps’ cause. Despite this, the problem continues owing in part to the potential for damage to harvesting head saws from stones if the cut is too close to the ground.

The innovation would be to utilise more robust felling equipment, most obviously shears, that can safely cut lower. It could be introduced in two possible ways. It could most readily be employed within bespoke biofuel systems where cut-stem integrity is less important and stem size likely to be limited. For full benefit, low-cutting shears would best be incorporated into efficient 'bunching' harvesting machinery, including within a whole tree system. Alternatively, stumps left after the removal of a timber crop could be cut closer to the ground in a separate operation.

3.3.6.2.2 Status of innovation

TRL is around 2 mainly because an efficient system for cutting close to ground level and handling the stumpwood has not actually been developed. Individual components are either already available or just coming onto the market, but integrated systems that are suitable to applications in typical UK sites are still to be fully evaluated.

3.3.6.2.3 Potential impacts

Yield The increase in yield is estimated on the basis of Forest Research experience to be 10-30% of the branch and stem top biomass for an individual tree.

Costs are not available. Harvesting costs are likely to be dependent upon whether this is introduced as a new integrated biofuel system or an additional operation following timber harvesting. In the former, a bespoke system should result in faster felling and biofuels collection; in the latter, costs are likely to increase and rely on the adaptation of current systems for collecting stems or residues from the harvesting site. There may however be lower establishment costs for the next rotation because of easier machine movement across the site.

3.3.6.3 Residue removal

3.3.6.3.1 Description

The essential improvement is to utilise as much of the fine branches and uppermost stem as possible within a silvicultural, harvesting and utilisation system. This innovation is compiled largely from existing technical options which could be combined to minimise operational costs and therefore machinery interventions. At its simplest, this innovation affects thinning (if applicable) and harvesting, but it may also impact on ground preparation for the following rotation.

Trials are required to optimise the integrated residue harvesting systems in a range of likely use cases and to clarify the site characteristics and circumstances where increases in yield justify the cost of additional operations to collect and remove a greater proportion of the residues. The innovation proposed is to develop comprehensive best practice guidance to ensure that increased residue removal is successful.

3.3.6.3.2 Status of innovation

TRL is 7. Removing residue as a biomass resource has been practised at least since the 1980s, when the bioenergy market started to emerge as a potential future forest revenue stream. Markets for utilisation as biofuel have developed but the operational systems are not optimised for a buoyant bioenergy market. Also, the supply chain is still very fragmented, opportunistic and somewhat *ad hoc*, so there is potential to specify one or more bespoke systems. Although there is some understanding of quantities available, extraction methods, costs, biofuel quality ranges and accepted environmental restrictions, comprehensive best practice guidance that balances these factors is needed if this innovation is to be successful. Key players in developing and implementing this innovation would be management companies, private sector foresters, and managers of the national forest estates.

3.3.6.3.3 Potential impacts

Yield There are clear yield benefits, with an additional 100 to 150 or more green tonnes per hectare available from conventional upland Sitka spruce plantations that can be extracted as an extension of the existing harvesting operations, whether by forwarder or by cable crane on steep ground.

Costs Extraction costs in UK LRF are known for residues collected from current operational thinning and harvesting systems, including through Forestry Commission studies, both as a secondary 'scavenging' recovery and as product of cable crane extraction. For example, £7 - £9 per green tonne (at 2019 prices) for forwarding in stated conditions. However, there should be further cost advantages in a well-designed, 'purpose built' system that puts greater emphasis on residue removal for bioenergy. This would have the additional advantage of reduced operational costs owing to 'clean' brash-free restocking sites.

As with other potential systems, GHG emission effects might be marginally positive, through reduction of 'unit-of-biomass' machine hours employed.

3.3.6.4 Stump and root removal

3.3.6.4.1 Description

The proposed improvement is to utilise as much of the stump and attached root system as possible within a silvicultural, harvesting and utilisation system. This is distinct from removal of the stump to ground level (see section 3.3.6.2). Stump and root removal was trialled in the UK some years ago but has not become an established practice for bioenergy supply, mainly because of environmental concerns. Nevertheless, stump and root removal is common in South East England as a way of limiting the root disease *Heterobasidion annosum* spreading to the next crop. Also, stumps are pulled out, if necessary, to clear the way for new forest roads and as noted by one stakeholder there is a potential opportunity for stump removal in heathland restoration areas where rugged ground is desirable. Moreover, stump and root removal techniques are well established in other countries.

The proposed innovation is to collect robust information on the system in the context of bioenergy supply as the basis for information and guidance. Extracting stumps requires specialized equipment and practices. Even setting aside the issues of soil disturbance and loss of soil carbon and organic content, the energy required to extract a stump and the attached large roots may not be justified by the biomass thus extracted. The basic technique and various equipment options need to be refined and evaluated for present day issues such as soil carbon and GHG emissions, as well as the impact on bioenergy production and costs.

This innovation affects harvesting. It might also be introduced at the same time as residue removal (see Section 3.3.6.3).

3.3.6.4.2 Status of innovation and key players

TRL is 7-8. Systems for removing stumps and attached roots have been trialled in the UK, mainly by private sector management companies.

3.3.6.4.3 Potential impacts

Yield If the site is suitable for stump and root extraction, the additional yield may be substantial – a rule of thumb is that the root system is approximately 30% of the above ground biomass. Estimates of total stump and root biomass are given in (McKay, 2003) but the amount extracted from an individual site is likely to be very variable depending on the species, age of crop and the site.

Costs are not available but are likely to be substantial albeit there may be a substantial yield. There may be lower establishment costs for the next rotation because of easier machine movement across the site.

3.3.6.5 Integrated harvesting system

3.3.6.5.1 Description

This innovation would involve the design of an integrated harvesting system that achieves an optimal balance between minimising machine costs and maximising machinery 'output' productivity to achieve a reduction in costs and GHG emissions. Such a system may require adjustments to silviculture and specification of forest-gate end-product. Crucially, any new harvesting system should, as far as practicable, utilise proven components, albeit potentially in new combinations, after which further development by innovation would be expected in practice. A number of stakeholders commented on how novel harvesting technologies, including feller-bunchers and long-reach shears for double row working, have the potential to improve operational efficiency.

This innovation affects thinning (if applicable) and harvesting but may also impact on ground preparation for the following rotation.

3.3.6.5.2 Status of innovation and key players

TRL is 2. Forest machinery is constantly evolving, although development tends to occur in occasional 'steps' followed by longer periods of evolution.

Key players The main players are a few largely Scandinavian, Japanese and American forest machinery manufacturers and, more locally, an array of forestry engineering firms and contractors who both import new types of machinery and innovate to deliver better, cheaper or more effective solutions to working.

3.3.6.5.3 Potential impacts

Yield Increase in yield can be achieved through harvesting more of each tree, such as poles with tops, or whole trees and harvesting material that would otherwise not be brought to market.

Cost The cost of a new harvesting system cannot be estimated. Reduced unit cost should accrue from increased system productivity, reduced machine cost or, most promisingly, a combination of the two.

GHG The GHG emission benefits would appear to derive primarily from increased biomass recovery from sites and the markets supplied, but overall there may be only marginal GHG effects owing to differences in machine hours involved in forestry operations.

3.3.7 Other innovations for existing forestry supply chains

Additional technical innovations that stakeholders suggested were:

- Exploitation of thinnings from natural regenerated coniferous sites. Upland sites (e.g. Kielder) with Sitka spruce can self-seed producing dense natural regeneration that could offer a good additional source of biomass. However, the trees are difficult to respace, and a considerable volume of unwanted material is produced (needles). An innovation which could remove the woody biomass and leave the needles behind would allow this opportunity to be exploited and reduce possible impacts on long-term site fertility.
- Understorey harvesting. A means of mechanically harvesting coppice species such as hazel, blackthorn, field maple and sweet chestnut when planting in the understorey of another species (e.g. ash) could increase uptake of this approach. For example, techniques (e.g. Bräcke head) which employ cutting rather than smashing or ripping hazel allows for regrowth from the cut stump. Even with such innovation, the approach is likely to require sites larger than 2 hectares to be financially viable.

However, the majority of innovations suggested by stakeholders were non-technical innovations that could help to improve efficiency, output and competitiveness. These included:

- **Information and training.** It was suggested that the wealth of information and experience available in non-commercial organizations such as Forest Research and the Forestry Commission should be made more widely available through training courses and information dissemination. There was felt to be a requirement for "boots on the ground" to help support landowners, such as through the Woodland Initiatives. This is required to help inform small landowners who are currently not connected with the forestry sector. High quality training could also help to create better quality contractors with better understanding of the needs and constraints of the bioenergy sector.

  It was suggested that publishing the national "available cut" might help to draw attention to the shortfall between the harvested quantity and the annual increment potentially available

- **Potential non-forest sources of biomass.** There are a number of potential sources of tree fellings that are not from conventional forestry. In many of these cases the difficulty is to ensure cost effective operations with relatively small quantities of widely distributed biomass. It was suggested that joined up working between different sectors with relatively modest biomass resources, such as the Highways Agency, rail networks and utilities, could together help to achieve sufficient scale for cost effective operation. The following potential sources were suggested:
  - Transport corridors.
  - Shelter belts
  - Diseased trees, such as Chalara infected ash or Phytophthora infected larch, though in some case this would require stringent precautions to prevent spreading of pests or infection.
  - Riparian sites to help with flood management
  - Peri-urban sites, combined with amenity benefits
  - Un-grazed common land.
  - Contaminated land
- **Contract growing**. It was suggested that contract growing on farms could help to provide an ongoing income for the landowner, based on the estimated final value of the crop. This would need to be Government backed for confidence.
- **Logistics optimization**. It was suggested that improved logistics management to ensure products are not transported further than necessary could help to improve cost effectiveness.

3.3.8 Innovations to expand the supply chain

Experts at Forest Research identified two potential types of innovations, which move away from conventional forestry practices, but if successful could expand the supply chain:

- trees in combination with poultry or grazing animals (Section 3.3.8.1
- trees in combination with other crops (Sections 3.3.8.2 and 3.3.8.3)

3.3.8.1 Trees in combination with poultry or grazing animal

3.3.8.1.1 Description

Trees have been introduced to open grassland to provide shelter or a more natural environment for free range poultry (layers and broilers hens), sheep and cattle. Trees have also been established to screen intensive poultry units with the added benefit of 'scrubbing' ammonia emissions from the poultry as air passes through downwind woodland.

Many past agroforestry experiments led to the conclusion that the timber properties of agroforestry trees were so poor (because of the much wider spacing, hence heavier branching and poorer stem form cf. traditional forests) that the system as a whole was less profitable than the animals alone or woodland alone. Since the emergence of a bioenergy market the traditional criteria might become less important justifying a re-evaluation of this system, particularly when combined with some of the potential innovations outlined for traditional forestry, e.g. choice of species (possibly to focus on species that are less palatable to the animals or grow well at wide spacing); choice of provenance; and ground preparation. The innovation suggested is to evaluate the costs and yields of biomass, and the impact on the poultry or other grazing animals and their management and the impacts on net GHG emissions.

This innovation would apply upstream but would require changes to established practices for ground/site preparation stage, planting and establishment and maintenance (mainly protection of the trees). The basic technique and equipment options need to be refined and evaluated for present day issues such as GHG emissions, as well as the impact on bioenergy production and costs.

3.3.8.1.2 Status of innovation

Large-scale free-range poultry operations could be regarded as demonstrating TRL 7 but at the moment the trees' productivity in free-range systems is not a major consideration so efficient bioenergy production from the agroforestry system is probably closer to TRL1-2. Key players who might be involved include suppliers of free-range chicken and eggs (e.g. Moy Park, Traditional Norfolk Poultry; Bronze Free-Range turkeys. Since the Woodland Trust already benefit through sales of free-range eggs, they might be a useful champion.

3.3.8.1.3 Potential impacts

Yield An informed guess is that the productivity of the tree component could be increased, perhaps by up to 30% with good selection of species, provenance and management.

Costs Plant costs are likely to be higher since planting stock will probably be larger than in standard forestry. Initial protection costs will be higher. Nevertheless, there is some evidence that the system overall can be profitable, e.g. David Brass, CEO of The Lakes Free Range Egg Company, advocates tree planting as an active part of farm management; having started tree planting trial schemes on his family farm in 1997 he has come to appreciate the commercial and welfare benefits that trees deliver. Harvesting costs are likely to be higher because of the heavier branching and more dispersed crop. Agroforestry with livestock comes with a risk to efficiency as pointed out by a stakeholder; there are high establishment costs when trees are grown with animals because it is difficult (costly/time consuming) to protect the individual trees.

3.3.8.2 Trees in combination with other plant crops

3.3.8.2.1 Description

Intercropping is a relatively common system in other parts of the world. Provided the system uses a suitable combination of tree species and arable crop for the site, greater total yields are possible because of the shelter provided by the trees and/or the greater overall use of the site's resources, in particular the soil volume and associated nutrients and water. Intercropping has not been adopted in the UK. This might yield large enough trees for efficient harvesting, whilst utilising the pre-canopy closure space for an annual crop. Note that trees in combination with a lower stratum biomass crop is covered in the following section.

This innovation would apply upstream but would require changes to established practices for the ground/site preparation stage, planting and establishment and maintenance (mainly protection of the trees).

3.3.8.2.2 Status of innovation

TRL 3. The main players are currently research institutes, e.g. Cranfield.

3.3.8.2.3 Potential impacts

Yield UK experience is very limited but (de Jalon, et al., 2018) compared poplar with cultivated crops, poplar, and conventionally cropped arable land and reported that the arable system was the most profitable (over the first 14 years, the mean yields of winter wheat, spring barley and oilseed rape in the agroforestry system were reduced by 15, 26 and 6% respectively compared to the mean of the purely arable plot). When environmental externalities were included however the agroforestry system provided the greatest benefit.

Costs Initial costs are thought to be proportionately similar to LRF on lowland sites. Harvesting costs are likely to be higher because of the heavier branching and more dispersed crop.

3.3.8.3 Trees with ground layer biomass crop

3.3.8.3.1 Description

To combine a relatively wide-spaced overstorey crop of trees, harvested on an SRF or LFR timescale, with annual biomass production from an inter-row cultivation of a ground layer herbaceous biomass crop, such as a shade tolerant grass. Reed canary grass may be one candidate. This innovation would require changes to established practices for ground/site preparation, planting and establishment and maintenance (mainly protection of the trees).

3.3.8.3.2 Status of innovation

TRL 3. Whilst agroforestry in the form of cultivation of food crops within a matrix of overstorey trees is a common production system in, for example, small scale farming in Africa, its adaptation as a large-scale 'silvi-herbaceous' biomass production system in the temperate zone could be a novel approach.

3.3.8.3.3 Potential impacts

Yield: There are good empirical reasons to suppose that a 'silvi-herbaceous' biomass would confer advantages but there are no robust data from UK situations.

Costs for each of the two component systems may be higher, but when combined there could be a 'cost sharing' benefit in addition to the value of the extra biomass produced. For example, complete cultivation of the tree planting site followed by annual cropping costs borne by the field layer component, will offset weeding costs. Tree harvesting costs are likely to be higher because of the heavier branching and more dispersed crop.

GHG emission effects might be marginally positive, through reduction of 'unit-of-biomass' machine hours employed, and possibly through increased photosynthetic activity compared with 'trees-and-weeds'.

3.3.9 Summary of innovations in forestry

A summary of the key technical innovations identified , together with key barriers they address is given in Table 3-6.

Table 3-6: Summary of innovations to address specific barriers

<table>
<tr><th>Challenge</th><th>Specific issue</th><th>Existing potential solution (needs to be re-examined for bioenergy production)</th><th>Innovative solution</th></tr>
<tr><td rowspan="2">Costs</td><td>Cost of operations compared to the value of products</td><td>• Based on existing knowledge increase production by:
– Choice of existing species
– Species mix
– Direct seeding
– Manipulation of spacing of existing species
• Re-evaluation of soil preparation to take account of trade-offs between growth and soil carbon
• Manipulation of cut-off diameter
• Improved information sharing especially from current bioenergy suppliers
• Utilisation of additional crop components:
– Harvesting residues
– Stump and attached root</td><td>• Increase production per hectare of LRF and SRF by:
– Choice of new species or provenance
– Genetic improvement
– Novel species mixes
– Direct seeding of new species
– Manipulation of spacing of new species
– Fertilisation with anaerobic digestate on forests for bioenergy
• Utilisation of a greater fraction of the above-ground stump (mainly LRF)
• For LRF, better understanding and modelling of dual timber/bioenergy production systems
• Integrated harvesting systems (mainly LRF)
• New bespoke harvesting equipment (mainly LRF)
• Agroforestry (trees + poultry or grazing animals)
• Agroforestry (trees + crops)</td></tr>
<tr><td>Cash flow</td><td>• Contracts between grower and end-user with staged payments</td><td>• Introduction of SRF
• Introduction of SRF at close spacing with thinning mid-rotation
• Introduction of additional early thinning in LRF
• Direct seeding within an agricultural setting requires less investment in bespoke equipment
• Modifications to grant support (see below)</td></tr>
</table>

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution
Costs	Grants cover only a proportion of set-up costs	• Some examples of payment for ecosystem services, in particular water quality, may be worth consideration.	• Not examined as outside scope of study but possible innovations include: – Additional payment for carbon sequestration – Additional payment for other relevant ecosystem services – Extension of grant support to cover bioenergy production from agroforestry
	Uncertainty of market for end products, time scales involved and market fluctuations	• Long-term government and/or end-user commitment to bioenergy	• Not within scope of study
	Scale of operation	• Land-owner cooperatives • Improved logistics	
Access	Access for harvesters, large equipment	• Review equipment developed in countries with more mature bioenergy culture	• Harvesting technology suited to smaller scale operations and UK conditions
	Physical infrastructure, such as hard standing	• Advice specific to bioenergy supply chain	• Not within scope of study
Feedstock properties	Ash content		• Improved understanding of impact of different species (especially Coniferous cf. broadleaved species), stem diameter, proportion of leaves/needles, time of felling.
	Moisture content	• In-wood passive utilisation of waste heat	
	Potentially desirable compounds such as fermentable sugars, or volatiles for biorefinery activities	• Existing R&D effort	• Not within scope of study. Further innovation would require collaboration with industry
	Availability of specialized, expensive machinery		• Integrated harvesting systems • Harvesting technology suited to smaller scale operations

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution
Availability of infrastructure /resources	Availability of trained labour force and contractors		• Extension of technical training to include bioenergy
	Availability of efficient feedstock drying equipment	• Review equipment developed in countries with more mature bioenergy culture	
	Availability of planting material	• Confidence in nursery sector that there is a medium to long term market	• May need additional research to develop efficient systems for novel species
Logistics	Bulky material expensive to transport and store	• In-wood drying • Compaction of residues and chips	
	Scale	• Improved information sharing from current bioenergy suppliers	
Properties of high yielding species	Frost tolerance	• Match choice of planting material to site conditions. • Increase understanding of risk-based approach	• Genetic selection
	Water demand	• Match choice of planting material to site conditions	• Evaluate water-use efficiency of high-yielding stock
Attitudes	Attitudes of landowners	• Build on existing social research of the factors influencing decision making in different owner types	• Introduce SRF systems that do not prevent reversion to arable land
	Attitudes of general public	• Improve communication about environmental benefits of both planting and harvesting trees for bioenergy	• Woodlands established using direct seeding may be more acceptable from aesthetic point of view
Tying up land	Long term commitment; May well not be allowed to revert		• Introduce SRF systems that do not prevent reversion to arable land
	New crop; new business model	• Advice specific to bioenergy supply chain using novel species and systems	
Land ownership	Range of ownership aims other than production forestry	• Improved communication about environmental benefits of both planting and harvesting trees for bioenergy	
	Fragmentation	• Land-owner cooperatives	

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution
Non-technical	Information and training	• One-stop, authoritative shop for information and advice	
	Utilisation of non-forest sources of woody biomass	• Utility companies, Network Rail and Highways Agency having experience and expertise in woodland management but biomass generally left on site	
	Contract growing	• Contracts between grower and end-user with staged payments.	

4 Annual crops and crop residues

4.1 Introduction

This section considers other bioenergy feedstocks within the scope of the study and assesses whether they might make a substantive contribution to future bioenergy supply, evaluating potential quantities which could be available and challenges to their use. Three sources are considered: crop residues, non-forestry sources of wood, and catch crop (i.e. crops grown between other crops in the rotation) suitable for anaerobic digestion.

4.2 Resource production and availability

4.2.1 Crop residues

Crop residues that arise on farms mainly comprise above-ground plant parts that are not the main product of the crop such as leaves (e.g. sugar beet tops) and/or stems (e.g. straw). They can also include below-ground plant parts, particularly for 'root' crops, e.g. potato tubers that are too small to be picked up by the harvester. Crop residues that arise during processing, e.g. waste from cereal processing and rejected potato tubers are not considered here as they usually arise off the farm and are therefore outside of the scope of the study.

The major crops[6] that leave residues that are of interest from an energy generation perspective are:

- **Cereals** (wheat, barley, oats): straw from cereals is often collected currently and used for a variety of purpose including energy generation; some is left for incorporation in the field.
- **Oilseed rape:** straw from oil seed rape is more brittle than cereal straw; while it is currently mainly chopped and incorporated into the soil, some is collected, baled and used for energy generation.
- **Potatoes**: the residue is the stem and leaves. For new potatoes, the haulm (the above ground stem and leaves of the plant) is available as a green residue on the field. In the case of main crop potatoes, the haulm (stem and leaves) is typically 'destroyed', or desiccated, at least two weeks before harvest, by flailing and/or application of an agrochemical.
- **Sugar beet:** the green tops of the plants are generally left on the field after harvest.
- **Legumes:** peas and field beans, of which field beans have the largest area, the residue is mainly the stem of the plant with some leaves; in years when forage crops are in short supply stems may be collected and baled for use as animal feed.
- **Field vegetable crops**: this covers a wide variety of crops, from brassicas such as cabbages and Brussels sprouts to leeks, cauliflowers, lettuces and herbs. The crop residue is mainly leaves, but can include stems, as for Brussels sprouts which has a woody stem. Residues from field vegetables are generally either incorporated into the soil or grazed in the field.

Table 4-1 presents estimates of crop residue quantities arising in the UK, based on Defra statistics for crop area and yield, and harvest indices from various sources. The crop residues are divided into dry residues (under 20% moisture content and used for combustion) and wet residues (variable moisture content, usually greater than 50%). Estimates of residues from field vegetables, are not estimated in Table 4-1, as yields and residue yields vary substantially across vegetables in this category and while total acreage is relatively large (117,000 ha in 2017 (DEFRA, 2018)), areas for individual species or types fall below the 100,000 ha used for inclusion in the table[6].

[6] Major is defined here as crops cultivated on more than 100,000 ha in the UK, based on data from (DEFRA, 2019)

Table 4-1: Estimates of crop residue quantities arising in the UK

Crop	Area in 2017 ('000 ha)	Yield of main product (t/ha, fresh weight)	Harvest index	Theoretical residue yield (t/ha, fresh weight)	Theoretical residue production ('000 t fresh weight)	Residue yield (collectable, based on 5-y average yield to 2012) t/ha, fresh weight) [7]	Residue production (collectable, based on 5-y average yield to 2012 '000 t fresh weight)	Available for bioenergy [8] ('000 t fresh weight)	Energy yield per tonne fresh weight (GJ/t)	Total energy resource (TJ)
Crops with dry residues										
Wheat	1792	8.3	0.51 [1]	8.0	14,290	3.4	6,093	1,394	14.1	19,656
Barley	1177	6.1	0.51 [2]	5.9	6,898	2.6	3,079	705	14.1	9,934
Oats	161	5.4	0.51 [2]	5.2	835	3.0	483	111	14.1	1,558
Oilseed rape	562	3.9	0.225 [3]	13.4	7,550	1.8	1,012	723	14.1	10,198
Beans	193	4	0.4 [4]	6.0	1,158	2.6	494	353	14.1	4,977
Crops with wet residues										
Potato	127	49	0.75 [5]	12.3	1,556	5.2	663	474	0.916	434
Sugar beet	107	83	0.7 [6]	35.6	3,806	15.2	1,623	1,160	0.431	500

Source: based on Defra statistics for crop area and yield (Department for Environment, Food & Rural Affairs, 2018) and harvest indices from various sources as indicated below

(1) (AHDB Cereals and Oilseeds, 2018).
(2) (AHDB, 2015). The harvest index for oats was assumed to be the same as for barley.
(3) (Morgan, et al., 2010). Value is the midpoint of a range of 0.2 to 0.25.
(4) Estimate based on expert knowledge.
(5) (Mazurczyk, et al., 2009). Central value from range of 0.7-0.8.
(6) Estimate based on expert knowledge.
(7) Cereals and oilseed rape: (Nicholson, et al., 2014). Other crops: theoretical residue yield adjusted using the ratio of theoretical to collectable residue yields for wheat.
(8) Availability for bioenergy assumes 71% of cereal straw has other uses or is already used for bioenergy and, of the remainder, 28.5% would not be for sale (Townsend, et al., 2018). For oilseed rape straw and residues from potato, sugar beet and beans, it is assumed that current usage is zero, and 28.5% would not be for sale.

The estimated quantities of residues generated in Table 4-1 cannot be assumed to all be available for bioenergy as there may be a number of other existing uses e.g. animal bedding, mushroom cultivation, insulating materials, paper manufacture, and energy generation (Baral & Malins, 2014). Even crop residues that remain in the field have value as they can supply nutrients, reduce the risk of soil erosion and contribute to soil organic matter (Baral & Malins, 2014).

The availability of **cereal straw** for bioenergy depends on factors including demand for other uses such as livestock bedding (both locally and regionally), and its use for soil incorporation. (Nicholson, et al., 2014) reported that 71% of straw in Great Britain was used across agriculture and horticulture, including use for bioenergy (mainly combusted, but with small amounts of wet straw used in anaerobic digestion), leaving 29% 'unused', presumably incorporated into the soil. More recent data are lacking, but stakeholder consultation indicated that use for bioenergy has increased, and that there may be a decrease in use for livestock bedding as farms in some areas have moved away from use of straw bedding in favour of sand.

There is large uncertainty about the willingness of farmers to divert incorporated straw to use for bioenergy. A survey in 2012 (Townsend, et al., 2018) showed that 28.5% of straw that was chopped and incorporated would not be sold even when payments were generous. The same survey also showed that some farmers were not willing to supply straw even where the straw could be removed sustainably, taking account of soil management. On-farm decisions were influenced by factors including timeliness of field operations and negative soil impacts associated with trafficking for baling and collection.

Most **oilseed rape and field bean** residues are believed to be incorporated into the soil, and no estimates of usage off the field could be found in the literature. For **sugar beet and potatoes**, residues are generally not removed from the field, but sugar beet tops may be used in field for livestock grazing.

The harvest or collection of crop residues may include cutting of stems, picking up previous cut material, collection into a trailer, baling in the field if needed, and wrapping to ensile the residues if needed. Storage may occur either on or off the farm.

4.2.2 Other residues

Arboricultural arisings consist of the residues produced from maintenance of domestic and municipal gardens, parks and off road, rail, canal and other transport corridors. Annual arisings in the UK have been estimated at 2.7 million odt (Mantau, et al., 2010), equivalent to 51,300 TJ. This resource is dispersed across the UK, often arising in relatively small quantities and in locations that have poor access for collection and removal. Some may contain large quantities of green material (leaves) or be contaminated with soil. About 45% is already estimated to be used for fuel wood (often in the domestic sector) and a further 20% chipped and composted (Mantau, et al., 2010).

Orchard fruit in the UK has an area of 24,000 ha. A report from Italy suggests that 1.1 odt per ha per year may be generated annually in the form of prunings, and 1.8 odt per ha per year from trees removed at the end of their productive life (an annualised estimate based on the total woody residues at the end of an orchard's life, divided by the number of years since planting) (Boschiero, et al., 2015; Boschiero, et al., 2016). This would suggest a UK resource size of 69,700 odt per year equivalent to 1,322 TJ per year. No data could be found in the literature on the fate of orchard prunings in the UK, but it is understood these are generally removed from the orchard for disposal. As orchards are often concentrated in particular regions of the country, this could be an additional, small, bioenergy resource which it is feasible to exploit. However further, more detailed investigation is required to confirm this.

4.2.3 Annual crop resources for anaerobic digestion

Conventional annual food and fodder crops grown for the purpose of anaerobic digestion (AD) feedstock are outside the scope of this study. However, an innovative approach of expanding the bioenergy resource for AD by growing catch crops between other crops in the rotation, has recently raised interest in UK. A high-level assessment based on published information on this subject has therefore been made for this study.

A catch crop is a crop grown between the time when a main crop is harvested and the time when the next main crop is sown. For example, following the harvest of a cereal crop (usually August or September in the UK), there can be a period of up to seven months before a following maize crop (for silage) is sown. A catch cop such as the cereal triticale could be sown in September and harvested as whole-crop for silage the following spring.

Catch cropping for AD has been tested in northern Italy and has had some success. Where the catch crop and the main crops are used for AD feedstock, there is no trade-off against production of other goods, usually food. Where the following crop is a food crop there may be such a trade-off; in the Italian system, double-cropping reduced output of the summer crop by 8% from harvest levels with no double cropping (Committee on Climate Change, 2018). In cooler climates such as in the UK, it can be expected that the benefits will be smaller because overwinter growth will be less than in lower latitudes. There is currently little evidence for the potential of this concept in the UK.

Assessing the potential area of land that could be used for catch crops, whilst minimising the decrease in production of main crops, is complex and not within the scope of this study. In principal it could be done using crop area statistics from surveys. Late-sown crops would need to be identified (e.g. forage maize, and some vegetable crops, possibly including some potato crops), and insight gained into the usual preceding crop and its harvest date. Winter oilseed rape and winter barley are usually harvested before winter wheat, and so may provide the best opportunities for catch crops. This analysis of potential area in the UK, and the trials needed to determine potential catch crop yields and effects on production of main crops, are data gaps which would need to be filled, before an accurate estimation of the potential resource available can be made.

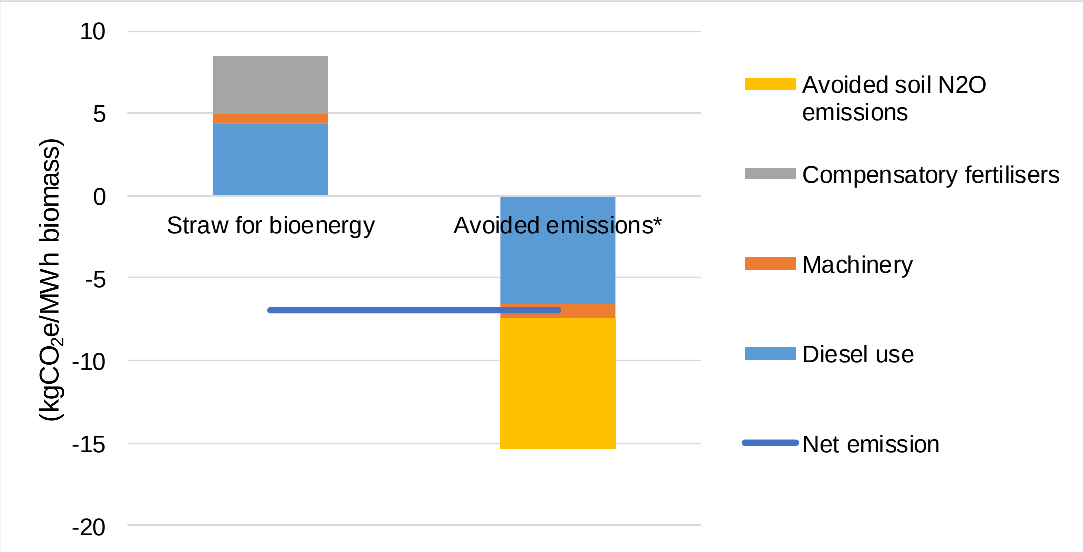
To give some indication of the potential area which might be suitable for catch cropping, in the UK maize was grown on 221,000 ha in 2018 (DEFRA, 2019). Potential yield by early April, when a catch crop could be harvested to allow subsequent establishment of maize, can be gauged by looking at winter wheat. This typically reaches 1.9 t/ha above-ground dry matter by 10 April, which is around 10% of the above-ground biomass produced by a mature wheat crop (AHDB Cereals and Oilseeds, 2018). Not all the above-ground biomass in April is likely to be successfully harvested without excessive soil contamination, because at that time in the UK the wheat plants grow close to the ground. Triticale and other cereals would be similar in this respect. Leaving harvest of a cereal catch crop until mid-May could increase biomass yield to around 7 t/ha above-ground dry matter (AHDB Cereals and Oilseeds, 2018) and harvest would be more practical than in April, but there will be a trade-off against the potential yield of a following maize crop. Further work is needed to analyse the potential trade-offs using typical yield data for the UK and knowledge of agronomy and soil conditions for sowing and harvesting.

4.3 Greenhouse gas emissions

In the case of crop residues, emissions from production are usually attributed to the main crop, as it is reasoned that this is the main reason for producing the crop. This is the approach taken in the GHG emissions methodology adopted in the Renewable Energy Directive and adopted with the UK's GHG sustainability criteria for fuels and heat and power produced from bioenergy. An alternative argument is that the crop residue, if it has a valuable use, should be considered as a co-product and some of the emissions from production of the crop should be apportioned to it – e.g. through mass, energy content or price.

In the assessment here, for wheat straw, the same approach is taken as in the analysis used as a basis for emissions from energy crops and SRF (North Energy, Forest Research and NNFCC, 2018). In this, only emissions from collecting and baling the straw are assessed (i.e. all production emissions are attributed to the wheat grain), but the emissions associated with the counterfactual i.e. where the straw would have been chopped and incorporated into the field are also assessed. This recognises that removal of straw may mean that additional fertilisation of the field is required to compensate for nutrients removed, but that there are emissions savings from not having to chop and incorporate the straw. Overall (Figure 4-1) this suggests that there could be a net GHG benefit from removing straw from the field, mainly due to the soil N_2O emissions which are avoided when the straw is not incorporated.

Figure 4-1: GHG emissions from collection of straw



* Emissions avoided due to no longer chopping and incorporating straw into soil

4.4 Costs

Costs of providing crop residues for use as a feedstock are those that are additional to the costs of crop production, These are principally the costs of collection and baling the residues and are estimated in (Table 4-2). The yields used to calculate these costs (from Table 4-1) are upper estimates of the quantities that can be collected, since, in practice, it is not possible to collect the total quantity present in the field. Variation in costs can be expected by variations in, for example, soil type and farm business structure; therefore, cost ranges are given in Table 4-2**: Costs of collecting crop residues, based on residue yields from**.

These data show that the costs per GJ are the same for all combinable crops, and this is because, for all combinable crops, we have assumed the same baling cost per tonne and the same energy yield per tonne. The costs per GJ for wet residues (potato and sugar beet) are greater reflecting the low energy yield per tonne. The energy yield for wet residues is low for two main reasons: the water content is high, and energy extraction is by AD, which extracts less energy per tonne than combustion.

Costs have not been estimated for catch crops as this production system is not yet well defined for the UK.

Table 4-2: Costs of collecting crop residues, based on residue yields from

Crop	Residue yield (collectable, based on 5-y average yield to 2012) t/ha (fresh weight)	Cost of baling[1] (cereals, oilseed rape and beans) or loose collection £/ha	Energy yield GJ/t (fresh weight)	Cost of baling £/GJ
Wheat	3.4	113 (94 – 133)	14.1	2.4 (1.9 – 2.8)
Barley	2.6	87 (72 – 101)	14.1	2.4 (1.9 – 2.8)
Oats	3.0	100 (83 – 117)	14.1	2.4 (1.9 – 2.8)
Oilseed rape	1.8	60 (50 – 70)	14.1	2.4 (1.9 – 2.8)
Beans	2.6	85 (70 – 100)	14.1	2.4 (1.9 – 2.8)
Potato	5.2	101 (88.78 – 111.20)	0.916	14.3 (12.6 – 15.8)
Sugar beet	15.2	101 (88.78 – 111.20)	0.431	11.2 (9.9 – 12.3)

Notes:
[1] For cereals, oilseed rape and beans: cost per bale is £6.67 (range £5.50 to £7.80; (SAC Consulting, 2018)), assuming 200 kg per bale. For potatoes and sugar beet, values are taken from (SAC Consulting, 2018), page 355, for forage harvester (whole crop).

4.5 Innovations

Few technical innovations were identified from the literature review or stakeholders. Points which were raised by stakeholders are discussed below.

4.5.1 Straw

Some stakeholders suggested that more use could be made of cereal and oilseed rape straw, but techniques and equipment for collection of these residues are well developed as it has been done for many years. Furthermore, the incorporation of straw (and other crop residues) into the soil is considered useful and of value by some farming businesses, and therefore, it can be argued that crop residues that are not collected are used. This was a position held by some stakeholders.

Where straw is being collected for use, stakeholders suggested that mapping to overlay power stations and production areas could encourage efficient straw collection and transport; this type of mapping has already been demonstrated in some places. Stakeholders also suggested that innovation in the design of supply contracts could increase the supply of straw feedstock, e.g. specifying a greater price for the last tonne than the first, and a bonus for delivering the full contracted quantity has been shown to increase supply.

It was reported in a Master's Thesis (Peng, 2018) that the high ash content of crop residues, relative to wood, can be reduced by minimising soil contamination at collection, and then by size fractionation and/or leaching (washing) in water. These latter two treatments add 30% to 66% to costs depending on the treatment combinations. This is a post-farm innovation, so is out of scope for this study but is included here for information. Another possible post-farm processing innovation is using torrefaction to densify and stabilise feedstocks, encouraging greater use and therefore more collection of residues.

One use of straw is for wintering carrots; around 100 t per ha is put onto the carrot field, leading to about 405,000 t of spent straw being available in England; little or none is available in other parts of the UK (Stakeholder, 2019). Spent straw after carrot harvest is partly degraded and suited to processing by steam explosion; this allows the extraction of higher-value components, with the remainder suitable for combustion. This is a potential additional use for straw.

4.5.2 Green crop residues

Innovations to allow practical collection of wet, or green, residues, such as sugar beet tops could open up a supply of feedstock for AD. Soil contamination is a barrier to use in AD plants, so methods are needed that allow collection with a minimum of soil contamination. Compaction and/or dewatering would facilitate handling and transport pf the residues to the point of use

4.5.3 Other residues

Orchard prunings could be an additional bioenergy resource, but a more detailed assessment of arisings in the UK and their current fate is needed to confirm this.

4.5.4 Catch crops

While the system of double cropping or catch cropping has been explored for warmer parts of Europe its feasibility in the UK is currently unproven. More work is required to analyse the potential trade-offs between current cropping practices and practices which include the use of catch crops, using typical yield data for the UK and knowledge of agronomy and soil conditions for sowing and harvesting. If this preliminary analysis shows that the use of catch crops looks promising, then field trials would probably be needed to determine potential catch crop yields and effects on production of main crops.

5 Assessing innovations

5.1 Screening of innovations for eligibility

As described in Sections 3 to 5, literature review and consultation with stakeholders identified a long-list of innovations that could help achieve an increase in the sustainable production of bioenergy feedstocks in the UK. The suggested innovations cover a wide range of potential actions -including some related to forms of support, training, data and information provision, and the first step in identifying key areas for support in any potential innovation programme was therefore to identify those options which would fit the remit of the competition. It is likely that any innovation competition would be part of the Energy Innovation Portfolio (EIP), and this requires that the technology readiness level (TRL) of the innovation must be between TRL 3 (applied research/proof of concept) and TRL 8 (first of a kind) i.e. innovations, which are still at a research or early pilot stage or are already commercially available, would not be eligible. Furthermore, it is necessary for the innovation to be of a technological or biological nature, or to have a substantial technological element. Each of the innovations identified was therefore screened against these two eligibility criteria.

In some cases, it was difficult to define if an innovation was technological or not, specifically measures that are not applied directly in the crop process but indirectly support the process, such as the creation of tools and information to support decision making. In these cases, it was considered that where a measure brings together and integrates different aspects of data (e.g. soil qualities) into an accessible tool to allow farmers to make informed decisions (e.g. better able to predict yield), it was sufficiently technical to be included.

The screening was initially performed based on the expertise of the project team and partners, and was then tested and refined with stakeholders at the workshop held in October 2019. Several innovations were screened out at this stage. Some were screened out as they were too high a TRL level – i.e. at TRL level 9 and considered ready for commercial deployment. Some were screened out as they overlapped or should be included amongst other innovations in the list. Some were screened out as being too low a TRL level – i.e. at TRL level 1 or 2 and hence at 'basic research' or 'technology formulation' levels, before first laboratory tests have been completed and proof of concept established. Although not eligible for this competition, there may be value in considering these innovations in other research programmes to ensure the 'pipeline' of innovations continues to develop. The innovations ruled out as having too low a TRL level are listed in Table 5-1.

Table 5-1: Innovations screened out because of low TRL level (1 or 2)

Sector	Innovation	Description of innovation
Forestry	Exploitation of thinnings from coniferous natural regeneration sites.	Section 3.3.7
Forestry	Trees in combination with other plant crops	Section 3.3.8.2
Annual crops and crop residues	Catch crops for use as feedstock for AD.	Sections 4.2.3 and 4.5.4
Annual crops and crop residues	Collection of 'wet' green residues, such as sugar beet tops	Sections 4.2.1 and 4.5.2

Some innovations were screened out as not having a strong technological or biological component, or requiring implementation post the farm gate or forest road, and these are listed in Table 5-2. Many of these were identified by stakeholders as ways of overcoming non-technical technical barriers, which they considered equally important as technical innovation if the production of bioenergy feedstocks is to expand substantially and rapidly. It could therefore be valuable to investigate these suggested innovations further and consider other ways in which some could be supported and implemented.

For some of the innovations suggested for crop residues, the technical element was considered to already be fully developed (TRL 9) so the innovation related to economic or market innovation and was therefore not considered eligible for any potential innovation competition.

Table 5-2: Innovations screened out as not meeting technical/biological remit of competition or for being post farm gate/forest road

Sector	Innovation
SRC	Production of high-value industrial compounds and feedstock for energy combustion have been identified but needs further R&D to develop commercial processing systems and identify best-practice agronomy and varieties.
SRC	Develop agronomic guidance and knowledge to support growers in benefiting from multi-functional benefits of energy crops. Flood mitigation: machinery development and testing altered harvest times to accommodate flood periods. Biodiversity: incorporate research evidence into agronomic guidance to inform growers in site-selection and management. Pollination: Willow breeding and planting to increase pollen and nectar from male varieties.
All energy crops	Development of recommended varieties lists as for other agricultural crops should include yield, pest and disease resistance, sex, senescence date, bud burst and flood or drought resilience
Energy crops	A pesticide register for farmers to use: there is currently a lack of available information easy to hand. Only poor information is available on which pesticides can be legally applied to Miscanthus and SRC. Similarly, only poor information is available regarding fertiliser requirements for the post planting phase.
All energy crops	Central, independent source of information and support for growers strongly recommended by stakeholders to overcome barriers to uptake, with a range of key criteria listed. Including economic and planning tools and support, best practice guidelines, training, independent advice, to engage with influential stakeholder groups.
All energy crops	An industry led energy crops levy board to make the sector more competitive by increasing the availability of impartial information and facilitating applied research.
All energy crops	National Energy Crop Centre as a central, independent source of information and expertise for farmers/grower focused on energy crops This national centre could also coordinate engagement with wide range of stakeholders and public with influence e.g. agrochemical companies, land agents. Government funded plantations should be established as part of the centre as well; this would provide demonstration capacity and build confidence with growers and farm influencers and be a location for R&D aspects.
All energy crops	Economic innovations: A range of economic innovations proposed involving Local Enterprise partnerships and Rural Development Funds to build capacity, fund pilot projects or provide capital grants for machinery.
All energy crops	Develop decision-support tools to inform growers of multifunctional benefits of energy crops in specific locations
All energy crops	Develop landscape or scenario-modelling tools to predict environmental benefits/impacts of bioenergy crops at range of scales, farm, catchment, region. For example, assessment of flood mitigation potential on a catchment basis; impacts of planting on water availability.
Forestry	Information and training to help support landowners, such as through the Woodland Initiatives. This is required to help inform small landowners who are currently not connected with forestry sector. High quality training could also help to create better quality contractors with better understanding of the needs and constraints of the bioenergy sector.
Forestry	Contract growing on farms could help to provide an ongoing income for the landowner, based on the estimated final value of the crop. This would need to be Government backed for confidence.

Sector	Innovation
Forestry	Improved logistics management to ensure products are not transported further than necessary could help to improve cost effectiveness.
Crop residues	Use of 'dry' residues (e.g. from wheat, barley, oats, oilseed rape and beans): on farm element of collection already well established so is market based innovation.
Crop residues	Use of straw that has been spread on carrot fields to protect carrots against frost in winter as an AD feedstock.
Crop residues	Innovation in the design of contracts to increase supply of straw feedstock, e.g. greater price for the last tonne than the first, and a bonus for delivering the full contracted quantity has been shown to increase supply.

The list of innovations which were considered to meet the overall eligibility requirements of any potential innovation competition are listed in Table 5-4 for perennial energy crops and Table 5-5 for forestry. Table 5-3 maps where each innovation falls in the production process for each feedstock. All of these innovations were taken forward for further detailed assessment.

Table 5-3: Mapping of innovations against bioenergy crop type and process step

Feedstock	Breeding	Planting	Establish-ment	Harvest-ing	Post-harvest	Rever-sion	General
Miscanthus	EC1, EC2	EC4 EC5 EC7 EC8 EC11 EC12		EC17		EC20	
SRC	EC3	EC6 EC9		EC16	EC21	EC19	
All energy crops			EC10 EC13 EC14	EC15 EC18	EC22 EC23		EC24 EC25 EC26
SRF	F3 F4 F6 F8	F12 F14 F16					
LRF	F1 F2 F5 F7	F9 F11 F13 F15		F19 F20 F21 F22			F18
All forestry		F10 F17		F23 F24 F25	F29 F30		F26 F27 F28 F31

Table 5-4: Energy crop innovations 'screened in' and carried forward for further consideration

Ref	Sector[a]	Theme	Description of innovation
EC1	M	Increasing yield and resilience in new varieties	Breeding/screening for rhizome cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including multi-site trials to test traits of interest. This also includes option of subsequently following plantlet pathways, grown from initial feedstock. Could focus on screening given extensive breeding already undertaken in US.
EC2	M		Breeding/screening for seed cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including multi-site trials to test traits of interest. This also includes option of subsequently following plantlet pathways, grown from initial feedstock.
EC3	SRC		Breeding/screening for range of traits: improved yield, climate and stress resilience (drought, flood, frost, marginal land), growth on contaminated land, biochemical varieties, delayed bud-burst, combustion qualities of product, palatability of crop to reduce damage by grazing.
EC4	M	Scaling up production of planting materials	Adapted machinery methods for Miscanthus seed production. Incorporates investment in sites and machinery.
EC5	M		Improved rhizome production, storage and transportation to maintain vigour.
EC6	SRC		Production sites for generating planting material need scaling up alongside innovative method development.
EC7	M	Planting machinery innovations to increase establishment success and productivity	Machinery, strategies for planting plug-plants to increase establishment success, widen planting window and reduce environmental impact e.g. biodegradable films (not plastic), automated planting systems.
EC8	M		Machinery development for automated rhizome planting.
EC9	SRC		Planting machinery improvements combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land.
EC10	M +SRC	Increased establishment success and expansion of planting window	Weed control: herbicide-free agronomy, cover crops, machinery development and testing e.g. mechanical and robotic weeders, cover crops.
EC11	M		Developing strategies to plant at different times of year (non-spring) e.g. autumn planting under plastic to extend the planting window.
EC12	Miscanthus		Development and testing of soil amendments for marginal or contaminated land.

Ref	Sector[a]	Theme	Description of innovation
EC13	M +SRC	Development of new pesticides	Pesticide development and testing combined with new cultivars with pest and disease resistance traits.
EC14	M +SRC	Updated guidance for growers	Fertiliser information and trials for micro and macro elements.
EC15	M +SRC	Innovations in harvesting machinery to improve efficiency and access to difficult sites	Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs.
EC16	SRC		Machinery development for marginal areas (small, wet or sloping sites) and for winter harvesting at wet sites e.g. track-based machinery.
EC17	M		Baling technology: improvement to increase bale density so reducing costs and evaluation of baling chipped material.
EC18	M +SRC	Increasing knowledge on optimal harvesting	Research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality.
EC19	SRC	Improvements in end-of life crop removal and alleviation of concerns over difficulties	End-of-life crop removal or re-planting strategies have been investigated at small-scale, but strategies need developing to minimise impacts on soil carbon and GHGs, including herbicide-free strategies. Successful strategies need demonstrating to growers.
EC20	M		
EC21	SRC	Improved storage and on-farm pre-processing	Development of mobile on-farm pelleting
EC22	M +SRC		On-farm pre-processing: needs R&D to design and test strategies and processes e.g. on-farm compaction or washing/leaching to improve feedstock combustion quality.
EC23	M +SRC		Development of optimised storage systems including on-farm storage to maximise feedstock quality and scale-up storage facilities.
EC24	M +SRC	Monitoring to improve yield and reduce costs	Development of diagnostic and predictive tools to increase yield e.g. soil mapping to predict yield and remote sensing/drones to monitor in-field crop vigour to inform management and harvesting.
EC25	M +SRC	Updated guidance for growers	Decision support and planning tools for use at farm scale level. E.g. a planning tool whereby farmers can put in their own figures, land area, land type and other data to get a first pass “look-see” as to how energy crops might work for them. Could include considering selection of appropriate energy crop and yield.
EC26	M +SRC		Multi-crop and multi-site trials for different climatic and edaphic conditions for new and current cultivars requires to develop best practice guidance with management strategies.

[a] M = Miscanthus. SRC= Short Rotation Coppice

Table 5-5: Forestry innovations 'screened in' and carried forward for further consideration

Ref	Sector	Theme	Description of innovation
F1	LRF-B	Species selection	Re-examination of species selected to consider attributes important from a bioenergy perspective such as 'energy growth', the amount of biomass that could be available for bioenergy, carbon stocks, GHG emissions, other environmental impacts, and moisture content at harvest.
F2	LRF-C		
F3	SRF B		
F4	SRF-C		
F5	LRF	Provenance choice	When plants from a given original seed source (provenance) are grown in a different location.
F6	SRF		
F7	LRF	Genetic improvement	Genetic selection uses the selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors.
F8	SRF		Genetic selection uses the selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors
F9	LRF	Mixed species stand	Biological innovation - choice of species - increased use of mixed species stands when establishing new LRF.
F10	All	Soil preparation by ripping	Mechanical preparation method used for dry soil and for soils that have a deep compacted layer that restricts root growth and plant development.
F11	LRF	Direct seeding	Process of sowing tree seeds by hand or machine, directly onto a prepared field/forest site; could include the use of for seed encapsulation techniques used for conventional agricultural crops to help improve establishment (inclusion of nutrients, pest deterrents etc).
F12	SRF		
F13	LRF	Changing initial spacing between trees	Closer spacing (up to a point) will result in more biomass per hectare, particularly on shorter rotations which could provide supplies of bioenergy more quickly.
F14	SRF		
F15	LRF	Fertilising crops using digestate from AD or wood ash	Digestate from anaerobic digestion , is a potentially low-cost, nitrogen-rich organic fertiliser resulting from the recycling of food waste, which could be applied to boost biomass production. In the context of forestry, as compared with arable biomass cropping, acceptable application is most likely within lowland fast-growing silviculture – that is broadleaved or coniferous SRF – within an agricultural rather than forest land setting.
F16	SRF		

Ref	Sector	Theme	Description of innovation
F17	All	Unconventional soil amendments for carbon removal.	Unconventional soil amendments for carbon removal: Biochar, olivine, basaltic minerals, mineral weathering.
F18	LRF	Remote sensing for crop monitoring and management	Advances (and cost reduction) in satellite imagery, LiDAR and UAVs (drones) may provide a way of monitoring woodlands.
F19	LRF-C	Manipulating cut-off diameter	Increase or decrease the stem diameter at which the uppermost cut is made separating recovered roundwood produce from tree tops left on site as brash.
F20	LRF	Removal of stump to ground level	The lowest cut is made at the point where the stem starts to swell out. The stemwood above this cut is removed from the site but material below this cut (the stump) is usually left on site. Depending on the extent of swelling, the remaining stump can be up to 40 cm high and represents potential additional biomass if the cut height is reduced.
F21	LRF-C	Residue removal	To utilise as much of the fine branches and uppermost stem as possible within a silvicultural, harvesting and utilisation system. This is compiled largely from existing technical options which could be combined to minimise operational costs and therefore machinery interventions.
F22	LRF-C	Stump and root removal	To utilise as much of the stump and attached root system as possible within a silvicultural, harvesting and utilisation system.
F23	All	Harvesting technology	Design of a harvesting system that achieves an optimal balance between minimising machine costs and maximising machinery 'output' productivity to achieve a reduction in costs and GHG emissions (i.e. innovations in systems integration).
F24	All	Harvesting technology	Design of harvesting machinery and strategies to allow extraction of material from difficult to access sites e.g. sites with steep slopes, reduce impacts from accessing land (e.g. soil compaction), small pockets of woodland. Also includes adaptations for conventional farming machinery to allow extraction from small pockets of woodland, strategies for harvesting currently undermanaged/overstocked mixed species woodland, and for removal of trees felled because of pest or disease.
F25	All	Understorey harvesting	A means of mechanically harvesting coppice species such as hazel, blackthorn, field maple and sweet chestnut when planting in the understorey of another species (e.g. ash) could increase uptake of this approach. For example, techniques which employ cutting rather than smashing or ripping hazel (e.g. Bräcke head) allows for regrowth from

Ref	Sector	Theme	Description of innovation
			the cut stump. Even with such innovation, the approach is likely to require sites larger than two hectares to be financially viable.
F26	All	Potential non-forest sources of biomass.	Potential sources of tree fellings that are not from conventional forestry. In many of these cases the difficulty is to ensure cost effective operation with relatively small quantities of widely distributed biomass. It was suggested that joined up working between different sectors with relatively small resources.
F27	All	Trees in combination with poultry or grazing animal	Trees have been introduced to open grassland to provide shelter or a more natural environment for free range poultry (layers and broilers hens), sheep and cattle. Trees have also been established to screen intensive poultry units with the added benefit of ‘scrubbing’ ammonia emissions. This innovation would apply upstream but would require changes to established practices for ground/site preparation stage, planting and establishment and maintenance (mainly protection of the trees).
F28	All	Trees with ground layer biomass crop	To combine a relatively wide-spaced overstorey crop of trees, harvested on an SRF or LFR timescale, with annual biomass production from an inter-row cultivation of a ground layer herbaceous biomass crop, such as a shade tolerant grass.
F29	All	Small scale on-site densification	Small scale on-site densification. For example, torrefaction or pelleting. Would need to develop small scale mobile equipment (sled mounted).
F30	All	Removal of moisture content/drying	Removal of moisture content/drying before transport through forced drying, possible solar options.
F31	All	Decision support tools	Decision support tools and platform to provide easy to access information on species, provenance and genetic material, tools to assess land suitability - all with a focus on production for bioenergy as well as conventional timber.

5.2 Multicriteria assessment of innovations against key criteria

A multi-criteria assessment method was used to explore the relative merits of the innovations in Table 5-4 and Table 5-5 and to provide a method of prioritising those that would best help achieve the competition objectives. Eight assessment criteria were identified linked to objectives of the programme (see Section 6),

- Impact on cost and profitability
- Impact on production risk
- Wider production impacts
- Applicability
- Timeframe and scalability
- Impact on GHG emission
- Wider environmental and social impacts
- Uncertainty

A further four aspects linked to competition design were also assessed.

- Size
- Timescale
- Industry capability
- Supply chain interest

A full description each of the criteria and the assessment criteria used for scoring innovations against them is given in Table 5-6.

Each innovation was scored by the study team against each criterion based on the evidence gathered through the extensive literature review and the analysis of cost and GHG emissions by process step. The scores were then reviewed for consistency and understanding of the criteria. These scores were then moderated through detailed discussions at the stakeholder workshop in October. Final scorings were then produced based on the initial scoring by project team experts and the workshop discussion. For innovations in the forestry sector, scores were also reviewed at an additional meeting held with Forestry Commission experts, as representation of the forestry sector at the stakeholder workshop was lower than for the energy crops sector. Details of the assessment for each innovation are given in Appendix 2.

Multi-criteria analysis (MCA) was selected as the assessment method of choice in this case. This was chosen given the long-list of innovations to assess, and the fact that there are multiple objectives for the innovation competition and multiple barriers preventing take up of bioenergy feedstocks in the UK. With multiple variables to consider whether innovations would be successful in promoting uptake of feedstocks, this lends itself well to MCA as a structure. However, it is important to note there are limitations to this approach:

- ***Ensuring common understanding of the criteria***: to ensure innovations are scored effectively and accurately, the criteria must be well defined and unambiguous. In addition, there may be risk of overlap between criteria (e.g. impacts on costs of production, and overall production potential). To minimise this risk, detailed descriptions were developed to define the criteria and scoring. Prior to scoring undertaken by project partners and at the workshop, detailed briefings and explanations of both were provided. Scorers were asked to provide explanations for the scores provided which were then moderated to ensure the criteria had been understood correctly.
- ***Ensuring consistency between scorings***: where different criteria are assessed by different project partners or workshop participants, there may be divergence in the understanding of the scoring system. All scorings were reviewed and moderated by the central team to ensure consistency in scoring across criteria

- ***Project partner or workshop scorings***: The scorings were reviewed at the workshop, and in some cases the workshop participants proposed alternative scoring to those in the initial scoring. In these cases, the workshop scorings were taken as the final score given industry stakeholders are in a more advantaged position to judge the relative merits of different innovations, and also given these were discussed by two different groups of stakeholders.
- ***Qualitative scorings are subjective and open to bias: as*** scorings were discussed at the workshop with stakeholders who could be involved in developing these innovations, this could potentially introduce bias. This was managed through the production of initial scorings by the project team, the arrangement of the workshop so measures were discussed in mixed groups, and by two separate groups, the chairing of these discussions to ensure all stakeholders could comment on all measures and moderation of the rationales for scoring after the workshop to review rationale for scoring.
- ***Scorings are not on a continuous scale:*** All scorings are based on qualitative assessment, and while the scorings aim to give a sense of the scale of benefit under consideration, the scores are not on a continuous scale. They do not therefore provide detailed distinctions between the merits of different innovations . However, this is appropriate in this case as the assessment is only intended to rank the innovations, highlighting those that may be more promising than others for encouraging bioenergy feedstock production and helping to assist in the definition of an appropriate innovation competition. Which innovations will actually be funded will be determined by the competition bidding process, which will contain its own evaluation process.

5.3 Calculating a production score and ranking the innovations

To support the design of the innovation competition, the scores developed under the MCA were then used to rank the innovations in order of their potential to support sustainable increase in biomass feedstock production in the UK. This ranking was developed only to identify priority areas and themes, and to help steer the structure and design of the competition. The rankings developed under this project will not be used to assess individual proposals submitted under any subsequent competition, nor offer a guide to which innovations will be funded or prioritised over others.

The MCA criteria were compared against the competition objectives to determine which criteria were likely to be most important in ensuring that innovations supported under the competition would help to meet the competition objectives. The following were identified as the most important criteria: (i) cost reduction, (ii) risk reduction, (iii), improvement in wider production and (iv) applicability across sites in the UK. Each criterion's qualitative scoring (ticks and crosses) was converted to a numeric score and these were then combined to create a score intended to reflect the potential for increased production from the innovation using the formula:

'(Cost reduction + Risk reduction + Improvement in wider production) x Applicability'

The scores for potential for increased production were then used to identify the most promising innovations, to assist in the design of the competition (see Section 6). The ranking assigned to the innovations on the basis of this score is shown in Appendix 2.

As a sensitivity, an alternative production score was tested that also included the scoring against GHG emissions reduction potential in the feedstock production process (criterion vi). The sensitivity testing suggested that the ranking of relatively few innovations changed with inclusion of this impact, and these changes were not significant enough to impact on the conclusions and recommendations regarding the design of the innovation competition.

Table 5-6: Multi-criteria analysis criteria against which refined shortlist of options were assessed

Criteria	Description	Guideline scoring boundaries	Example scoring
i. Impact on cost and profitability	Does the innovation impact on the cost per tonne of production? This could be either through a direct impact on a cost input, or through an impact on yield. If so, how large is the impact?	- = Neutral / no impact ✓ = Low impact = <5% reduction in cost / increase in yield ✓✓ = Medium impact = 5-20% change ✓✓✓ = High = >20% increase in yield / reduction in cost	EC7 (planting machinery for miscanthus plug-plants) scored 'high': it was considered this innovation could impact on yield, feedstock quality, could expand the planting window and reduce planting costs directly, all of which would influence production costs EC14 (fertiliser information and trials for energy crops) scored low: fertiliser is only a small part of the overall production cost structure
ii. Impact on production risk	Does the innovation impact on the risks around production? Specifically, does this impact on the probability or risk that the landowner / manager does not achieve the expected yield and profitability? Note: to avoid overlap with 'i', we have assumed that any impact on the 'central' or 'best case' view of cost, yield and profitability is captured under 'i'. 'ii' concerns impacts on risks/sensitivity around that central assessment.	- = Neutral / no impact ✓ = Low impact = minor reduction in risk for farmer, but doesn't really change perception ✓✓ = Medium impact = moderate change, may impact on planting decision ✓✓✓ = removes significant / all risk from farmer	EC3 (SRC breeding innovation) scored high: breeding offers the opportunity to reduce production risk through susceptibility to for example climate events, floods, disease (e.g. ash die back), rabbit and deer protection. EC15 (cutting blades for energy crops) scored no impact: as although measure could have high impact on costs, it was considered innovation would be unlikely to change perception of risk by farmer
iii. Wider production impacts	Aside for cost/commercial and risk considerations, could the innovation provide any wider benefits to work towards the objective of sustainable increase in bioenergy production? E.g. could the innovation open up new technically feasible areas of production? Are any other physical barriers to scaling up (e.g. planting material availability). To avoid overlap with 'i', this, impacts on commercial viability, yield and risk are not included here	- = Neutral / no impact ✓ = Low impact = <5% increase in potential production scale ✓✓ = Medium impact = 5-10% increase in potential production scale ✓✓✓ = High = >10% increase in potential production scale	F3 (species selection in SRF Broadleaves) scored high: Developing high yielding species that are more frost tolerant and resistant to cold weather will help to extend the range northwards F9 (LRF mixed species stand) scored no impact: innovation scored high for criteria I and ii, with no additional impacts on production outside these benefits

Criteria	Description	Guideline scoring boundaries	Example scoring
iv. Applicability	Can this be applied to all potential production sites or only some?	'-' = NA or no limitation to application x = Low = Minor limitation - can still be applied to most plantations >50% xx = Medium some limitation, can only be applied to 25-50% of cases xxx = High = severe limitation, only applies to <25% of cases	EC18 (increasing knowledge on optimal harvesting for energy crops) scored no impact: as innovation could be applicable to all energy crop sites with no limitations EC21 (on farm pelleting for SRC) was scored high - severe limitation: given the market for pellets is very narrow, it was considered that the number of sites where this is applicable would be much fewer than other innovations
v. Timeframe and scalability	What is the timeframe before a successful innovation project will start delivering a benefit for farmers/landowners/managers? As an illustration, could apply to existing plantations, or can only be adopted for new conventional plantations, or indeed would require additional research needed before it could be implemented? Furthermore we also consider how quickly the innovation can be taken up by bioenergy production sites.	- = Neutral / no impact ✓ = Long = 20-40 ✓✓ = Medium 5-20 ✓✓✓ = Immediate = <5 years	F23 (harvesting technology for forestry) was scored immediate: as once developed, technology could be used immediately on existing plantations, but would require some time to develop the innovation and modify machinery F11 (LRF provenance choice) was scored long-term: once innovation project is complete, it then requires implementation at new or re-stocking plantation, and benefits would not be seen until harvesting in 20-40 years' time
vi. Impact on GHG emission	What is the potential impact on GHG intensity of production? Here we have focused on impacts in terms of tCO_2e / GJ produced. These impacts could be positive or negative, and could capture direct impacts (e.g. on fuel consumption) and through impacts on yield	x = Low increase = <5% xx = Medium increase = 5-10% change xxx = High increase = >10% change - = Neutral / no impact ✓ = Low reduction = <5% ✓✓ = Medium reduction = 5-10% change ✓✓✓ = High reduction = >10% change	EC5 (scaling up miscanthus rhizome production) scored low as reduced losses will reduce GHG emissions associated with production, transport and planting, but impact is likely to be small F1 (species selection for LRF – Broadleaved scored high: Increased growth rates will increase sequestration
vii. Wider environmental and social impacts	Does the innovation bring any other benefits? How significant are they?	x = Low = minor additional impacts (negative) xx = Medium additional impacts (negative) xxx = High additional impacts (negative) - = Neutral / no impact ✓ = Low = minor additional impacts (positive) ✓✓ = Medium additional impacts (positive) ✓✓✓ = High additional impacts (positive)	F22 (stump and root removal of Coniferous) scored medium negative: can be considerable impact on ground damage, soil carbon loss, nutrient sustainability and acidification F23 (optimal forestry harvesting systems): scored high positive: Low ground pressure systems can allow reduced soil compaction and damage; Smaller machinery can allow more effective thinning in sensitive sites with minimized damage to other trees; and alternative cutting technologies can reduce damage to cut end of log and stool/stump

Criteria	Description	Guideline scoring boundaries	Example scoring
viii. Uncertainty	What are the uncertainties around innovation and its impacts? How certain are we that the innovation will deliver the benefits / improvements listed?	✓ = Low/no uncertainty around impacts, have evidence in literature / from other dependable source - = Moderate uncertainty around key criteria x = High uncertainty in performance against key criteria	EC19 (SRC end of life crop removal) scored low: There is a lot of existing experience across the sector with individuals/companies, but very little published or promoted commercially EC12 (testing soil amendments for miscanthus growth on marginal land) scored high uncertainty: Considerable uncertainty around marginal and contaminated land - requires R&D and then commercialisation
a) Size	What size of project would be required?	• Small <£500k • Medium £500k - 2m • Large >£2m	
b) Timescale	How long would it take to fully develop the innovation?	• Could demonstrable progress be made in a three- to five-year timeframe? • What would that progress look like	
c) Industry capability	Could the innovation be developed within the UK?	• Wholly • Partly • Little UK capability	
d) Supply chain interest	How much interest is there in this innovation within the supply chain?	• Low • Medium • High	

Alongside ranking the criteria by production score, the ranked shortlist was further refined according to likely duration of the innovation project (criterion b)). This was to identify the innovations that could be fully supported within a typical spending review cycle (assumed to be three years). All innovations that could be delivered in less than 3threeyears were included, in addition to those that were assessed as lasting three to five years (as it was considered possible, they could deliver some results inside three years). As such, some innovation projects which were identified as requiring a project duration greater than five years were removed at this stage. As with the innovations screened out at the screening stage, this is not to say that these innovations would not provide a valuable contribution to the feasibility of increasing bioenergy feedstock growth in the UK. Indeed, some of these are likely to be important for longer term impacts and continued development of supply chains. The removal at this stage simply reflects they would not be eligible for support through an innovation competition funding route within the remits proposed by this feasibility study. These innovations may be more suitable for funding via routes which are able to offer longer term funding. The measures screened out are:

- EC3 – breeding and screening in SRC
- EC26 – developing updated guidance for energy crop growers based on multi-site trials
- F13 – changing initial spacing between trees in LRF plantations
- F26 – exploring non-forest sources of biomass – i.e. not from conventional forestry.

The scores against other MCA criteria were used in programme design to check for other impacts, including:

- Average project duration and budget,
- Level of uncertainty in the available data on impacts,
- Level of impact on GHG emissions (both negative and positive),
- Current industry appetite for specific innovations, recognising that the market and other drivers could change within the next 18 months ahead of the launch of a new innovation competition and
- Other wider environmental impacts such as flooding risks, resilience and biodiversity.

In the case of GHG emissions, the analysis in Sections 2.3, Section 3.1.2 and Section 3.2.2 has shown that production of these feedstocks is typically low carbon. However innovations were still scored against a GHG emissions criteria as it is important that any innovation does not lead to a significant increase in production emissions and ideally should maintain them at current levels or ideally reduce them.

6 Design recommendations for a future innovation competition

Key steps in the design options review were:

1. Establish fixed programme-level objectives vs. flexible competition-level objectives.
2. Establish variable parameters such as budget, timescale for implementation, timescale for impact realisation, type of programme and number of competitions.
3. Produce a ranked list of 50+ innovations from the MCA based on fixed programme-level objectives and review the options for grouping those innovations.
4. Review the ranked list of innovations against each of the variable parameters, noting pros and cons of different options, the impacts on the ranked list, and the impacts on the achievement of the programme-level objectives.

Relevant commentary from key stakeholders was included where it could influence the recommendations, to provide BEIS with all relevant information, and to reduce any potential bias in the work.

The programme-level objectives were agreed with BEIS at the kick-off to the project and were re-agreed at the beginning of the programme design phase Task 3 to ensure consistency had been maintained. The primary source of the programme-level objectives was the overarching **aim** of the Energy Innovation Portfolio to reduce the UK's carbon emissions and the cost of decarbonisation by accelerating the commercialisation of innovative clean energy technologies and processes into the mid-2020s and 2030s.

The five fixed programme-level objectives are:

1. **To increase the amount of sustainable biomass feedstocks produced in the UK.**
   This objective was treated as a broad goal without a specific target or timescale. Once the future competition has been fully designed, the final competition objective should define a target for the amount of feedstock production, and a timescale for achieving the target, ideally against a baseline of a' business as usual' projection.
2. **To reduce the GHG emissions associated with biomass production up to the farm gate or forestry road.**
   This objective was treated as a broad goal, with a similar recommendation of defining a target or range of reduction in the final competition objective.
3. **To reduce the cost of biomass production up to the farm gate or forestry road.**
   This objective was treated as a broad goal, with a similar recommendation of defining a target or range of reduction in the final competition objective.
4. **To improve the resilience of UK resources to future climate change impacts.**
   This objective was added as a result of the input of the Task 3 Advisory Board.
5. **To fund projects that accelerate the commercialisation of innovative technologies and processes.**
   This objective was linked to SICE funding requirements for innovation competitions. Deployment of existing off-the-shelf technology would not fulfil the objectives of the programme.

The ability for innovations in sustainable biomass production to simultaneously achieve more than one objective was noted during the MCA in Task 2 of the study (e.g. reducing the cost of biomass production would logically lead to an increase in amount produced), and all screened options were assessed against their ability to achieve the objectives individually.

6.1 Overall summary of recommendations

The work completed under the study allows for a conclusion that a future competition to support innovation in the area of biomass production would be feasible, have sufficient interest from the industry, and sufficient innovation potential to significantly increase sustainable biomass production in the UK.

In completing the scenario analysis, the key factor influencing recommendations for the number of projects and likely impact of the competition was the overall funding budget. Ultimately, the budget that SICE approves for any future innovation competition will determine the recommended competition design. In the following section, recommendations are made in three budget scenarios, with key decision pathways stemming from that point.

Throughout the scenario analysis we have used the following colour coding to indicate ratings for objectives and risks:

Objectives rating	Risks rating
Highly likely	Unlikely
More likely	Less likely
Likely	Likely
Less likely	More likely
Unlikely	Highly likely

6.1.1 Recommendation in a low budget scenario (£10m)

Scenarios A1 to D examined a low budget (£10m) scenario through a number of sensitivities as shown in the summary table below.

Table 6-1: Low budget (£10m) scenario analysis

Scenario	A1	A2	B1	B2	C	D
Budget	L	L	L	L	L	L
Sector	Energy crops	Forestry	Energy crops	Forestry	Neutral	Neutral
Timescale	Short	Short	Medium	Medium	Short	Medium
Programme type	Targeted	Targeted	Targeted	Targeted	Targeted	Targeted
Ability to meet objectives						
Increase amount of UK production						
Reduce GHG emissions						
Reduce cost of production						
Improve resilience to future climate change impacts						
Acceleration of innovative technologies						
Likelihood of key risks occurring						
Failure to recruit sufficient applications						
Technology supply chain bottlenecks						
Sites are not sufficient to demonstrate impact						

The key recommendation in a low budget scenario is to run a competition that funds a single sector, supporting energy crops, with projects that have impacts ranging from 2025 to 2045 (**scenario B1**) in order to have maximum impact on future UK production of sustainable biomass.

Why single sector? Although this appears to go against the findings of the scenario analysis (i.e. scenario D has the most positive assessment), taking a sector neutral approach in such a low budget scenario risks diluting the impact of the overall programme, by only funding 3-4 projects from each sector. The recommendation to focus a low budget competition on a single sector reflects the stakeholder feedback that ramping up future UK production needs to address multiple supply chain stages, which would be difficult to achieve if the budget were diluted across two sectors.

With that said, if funding was focussed solely on the innovation categories with the highest production scores across both energy crop and forestry innovations (a production score higher than 8/10), the competition could still have a relatively high impact on future UK production in specific areas of the supply chain.

Why energy crops? As can be seen in Appendix 3, when all innovations are ranked by production potential scores, innovations in energy crops dominate the top of the list. If the competition was to focus on a single sector, based on the underlying assumptions in the method used to calculate the production score, projects that deliver under the top scoring innovation categories will have the highest impact on future UK production.

Why medium-term impacts? The SICE objective, to fund projects that accelerate the commercialisation of innovative technologies and processes, has a better likelihood of being achieved when project impacts could be realised up to 2045. A competition with a short-term impact focus (up to 2030) is more likely to fund projects at a higher TRL level with them becoming commercially available by 2024/25. Even though this would clearly be beneficial to the sector overall, this approach would not accelerate technologies at lower TRLs in the same way. The implications of timescale selection on potential impacts is discussed further in Section 6.2.

What types of innovation should be included? A further recommendation would be to specify the categories of innovation that the competition would fund, in order to maximise the delivery of high potential productivity impacts in line with the top-ranking innovations in the MCA. The suggested categories (based on production scores of more than 5) would be:

- (EC5 + EC6) Innovations that scale up production of planting materials, e.g.
  - Innovations related to improved rhizome production, storage and transportation
- (EC8 + EC9) Planting machinery innovations to increase establishment success and productivity, e.g.
  - Planting machinery innovations combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land
  - Machinery development for automated rhizome planting
- (EC15 + EC17) Innovations in harvesting machinery to improve efficiency and access to difficult sites, e.g.
  - Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs
  - Innovations in baling technology
- (EC1 + EC2) Innovations that increase yield and resilience in new varieties, including breeding/screening for rhizome or seed cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including trials to test traits of interest
- (EC23) Innovations in storage, e.g. development of optimised storage systems including on-farm storage to maximise feedstock quality and scale-up storage facilities
- (EC18) Increasing knowledge on optimal harvesting and guidance for growers, through research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality, and improved decision support and planning tools at a farm-scale.

How many projects could be supported? It is important to note that the recommended categories of innovation above set out the types of innovation most likely to have a positive impact on future UK production of biomass. The £10m budget could fund between 10 and 20 projects spread across the range of categories, with estimated project budgets for innovations in the above categories ranging between £500k and £3m (50% funding would equate to grants between £250k and £1.5m).

6.1.2 Recommendation in a medium budget scenario

Scenarios E to H examined a medium budget scenario (£20m) through a number of sensitivities as shown in the summary table below.

Table 6-2: Medium budget (£20m) scenario analysis

Scenario	E	F	G	H
Budget	M	M	M	M
Sector	Neutral	Neutral	Neutral	Neutral
Timescale	Short	Short	Medium	Medium
Programme type	Targeted	Multi-site	Targeted	Multi-site
Ability to meet objectives				
Increase amount of UK production				
Reduce GHG emissions				
Reduce cost of production				
Improve resilience to future climate change impacts				
Acceleration of innovative technologies				
Likelihood of key risks occurring				
Failure to recruit sufficient applications				
Technology supply chain bottlenecks				
Sites are not sufficient to demonstrate impact				

The key recommendation in a medium budget scenario is to run a competition that splits funding into two streams with a suggested £15m for energy crops and £5m for forestry based on the top ranked innovations in **scenario G**, with projects that have impacts ranging from 2025 to 2045 in order to have maximum impact on future UK production of sustainable biomass. Scenario G was selected due to the overall level of likelihood in achieving the competition objectives, balanced with the likelihood of key risks occurring.

Why split the funding? Analysis of the production scores for both sectors showed forestry and energy crop innovations had relatively equal potential to have a positive impact on future UK biomass production. To fund equal numbers of projects in each sector, the competition design would need to consider the average project budgets for the different sectors. The average project budget for most forestry innovations is less than £500k (funded at a grant intensity of 50% would mean grant awards of less than £250k per project). When compared to the average energy crop budget of £1-2m (grant awards of £500k-£1m per project), this led to the recommendation of splitting the £20m funding to £15m for energy crops and £5m for forestry, otherwise the split of projects could be overtaken by one of the sectors. The recommendation also reflects stakeholder discussion of this point in the Task 3 workshop.

This recommendation has been introduced for a medium budget scenario, although it could be equally applied to the low budget scenario if a sector neutral approach is decided (scenarios C or D).

Why medium-term impacts? The SICE objective, to fund projects that accelerate the commercialisation of innovative technologies and processes, has a better likelihood of being achieved when project impacts could be realised up to 2045. A competition with a short-term impact focus (up to 2030) is more likely to fund projects at a higher TRL level with them becoming commercially available by 2024/25. Even though this would clearly be beneficial to the sector overall, this approach would not accelerate technologies at lower TRLs in the same way.

What types of innovation should be included? The recommendation to list specific categories of innovations remains valid, with the suggested list of energy crop categories from the low budget scenario continuing to be the core list of energy crop innovation categories that are recommended for inclusion in the competition:

- (EC5 + EC6) Innovations that scale up production of planting materials, e.g.
    - Innovations related to improved rhizome production, storage and transportation
- (EC8 + EC9) Planting machinery innovations to increase establishment success and productivity, e.g.
    - Planting machinery innovations combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land
    - Machinery development for automated rhizome planting
- (EC15 + EC17) Innovations in harvesting machinery to improve efficiency and access to difficult sites, e.g.
    - Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs
    - Innovations in baling technology
- (EC1 + EC2) Innovations that increase yield and resilience in new varieties, including breeding/screening for rhizome or seed cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including trials to test traits of interest
- (EC23) Innovations in storage, e.g. development of optimised storage systems including on-farm storage to maximise feedstock quality and scale-up storage facilities
- (EC18) Increasing knowledge on optimal harvesting and guidance for growers, through research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality, and improved decision support and planning tools at a farm-scale.

Additionally, scenario G includes forestry innovations and would therefore lead to the recommendation to include the following innovation categories:

- (F3 + F4) Innovations in species selection for SRF and LRF Broadleaved and Coniferous, e.g.
    - Selection of species according to rapid volume growth and good stem form
    - Alternative species selection considering attributes important from a bioenergy perspective such as 'energy growth', the amount of biomass that could be available for bioenergy, carbon stocks, GHG emissions, other environmental impacts, moisture content at harvest
- (F31) Decision support tools and platforms to provide easy to access information on species, provenance and genetic material, tools to assess land suitability
- (F24) Innovations in harvesting technologies, including design of harvesting machinery and strategies to allow extraction of material from difficult to access sites
- (F8) Genetic selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors

How many projects could be supported? The £15m budget for energy crops could fund between 15 and 25 projects spread across the range of categories, with estimated project budgets for innovations in the above categories ranging between £500k and £3m (50% funding would equate to grants between £250k and £1.5m). Within a suggested budget of £5m for forestry, an estimated 15-20 individual projects could be funded from the categories above. Of all the forestry innovation categories, innovations in species selection and decision support tools scored the highest for production potential, so a recommendation would be to prioritise funding at least 5 projects in those two categories to gain maximum impact. All categories would be open for applications, as stakeholder feedback has shown it is important to fund projects across the supply chain stages, this approach simply allows BEIS to pre-select a minimum number of projects in the two areas of innovation with the highest potential for impact. This approach has been used in recent BEIS Energy Innovation Programme funds, such as the Boosting Access for SMEs to Energy Efficiency (BASEE) competition, where BEIS decided to ensure certain types of project were funded by creating minimum funding levels in particular categories. Bidders could still apply for funding in all 3 categories set out in the BASEE competition, in the knowledge that BEIS would definitely fund at least 4 projects in two of the categories, subject to applications reaching the minimum quality requirements.

6.1.3 Recommendation in a high budget scenario

Scenarios I to N examined a high budget scenario (£30m) through a number of sensitivities as shown in the summary table below.

Table 6-3: High budget (£30m) scenario analysis

Scenario	I	J	K	L	M	N
Budget	H	H	H	H	H	H
Sector	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
Timescale	Short	Short	Medium	Medium	Long	Long
Programme type	Targeted	Multi-site	Targeted	Multi-site	Targeted	Multi-site
Ability to meet objectives						
Increase amount of UK production						
Reduce GHG emissions						
Reduce cost of production						
Improve resilience to future climate change impacts						
Acceleration of innovative technologies						
Likelihood of key risks occurring						
Failure to recruit sufficient applications						
Technology supply chain bottlenecks						
Sites are not sufficient to demonstrate impact						

All scenarios show a £30m competition as having a high likelihood of increasing the amount of sustainable biomass produced in the UK. The main recommendation in a high budget scenario is to run a competition that splits funding into two streams (with a suggested £20m for energy crops and £10m for forestry based on the top ranked innovations in scenario N), including a multi-site demonstration workstream for specific energy crop innovations, with projects that have impacts ranging from 2025 to 2065 to maximise impact on future UK production of sustainable biomass.

Why split the funding? The same considerations for splitting the budget in the high budget scenario apply as for the medium budget scenario, i.e. to maximise impact across both sectors.

Why include demonstration sites? A multi-site demonstrator could provide focus on the demonstration of innovations for certain sectors (such as SRC), which would sit well within a larger programme in a high budget scenario. An open or targeted competition could be run with a multi-site demonstrator built into the competition design to encourage an integrated approach to benefitting the full supply chain.

Prescribing specific demonstration sites for certain energy crop innovations would ensure that innovations were assessed over sites that cover a range of UK climatic and soil conditions, providing valuable information about the improvements innovations could deliver under a range of conditions that might be encountered in practice. Focusing implementation on these sites would also mean that interactions and potential synergies between innovations in different parts of the supply chain could be identified and assessed. For example improvements in harvesting technologies or strategies could be tested not just against existing varieties but also new varieties developed under the competition. A demonstration site approach would be more appropriate for energy crops rather than for forestry, given the rate of growth for both short and long-rotation forestry, and that demonstration of short-term innovations (such as harvesting machinery) would not be necessarily linked to a specific site. A demonstration site approach is not recommended for innovations that have no specific link to climatic or soil requirements such as innovations in decision support tools or baling machinery, for example.

Additionally, it is important to note a competition without a multi-site demonstration component would still be highly likely to create positive impact, with good geographic coverage of climatic conditions and soil type, and without BEIS paying for additional management fees to set up and oversee multiple demonstration sites.

Why is a multi-site demonstrator only recommended in a high-budget scenario?

A multi-site demonstrator was ruled out for a low-budget scenario as it would be more costly to run and would therefore impact the number of projects to be funded in a low-budget scenario. In the medium-budget scenario, the combined risk of a demonstrator taking a disproportionate amount of the overall budget, with fewer projects funded in categories that were not appropriate for demonstration sites, along with a risk that applicants are not located geographically close to the selected sites, would potentially reduce the number of bids received.

Lessons learned from current EIP competitions included challenges in multiple projects completing to the same deadline on a single test site, which led to the recommendation that a multi-site demonstration would be best situated within a larger programme, that funds a significant number of projects outside the demonstration site workstream.

What is the implication of funding projects with long-term impacts (2065) rather than short- or medium-term impacts? In terms of practical management of project deliverables and outcomes, there is little difference between projects with medium- and long-term impacts, as both scales will be challenging to monitor the outcomes of the project, other than interim progress milestones within the lifetime of the competition budget. Unless BEIS is able to set up a long-term evaluation framework (lasting 5-20 years) there will be inherent risk that projects do not realise their estimated benefits until many years after the initial funding is paid. Climate change will also play a significant role in benefits realisation, although projects with both medium- and long-term impacts are generally rated medium/high in their ability to improve resilience to future climate change impacts.

What types of innovation should be included? Recommended categories of innovation for a multi-site trial would be:

- (EC1 + EC2) Innovations that increase yield and resilience in new varieties, including breeding/screening for rhizome or seed cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including trials to test traits of interest
- Potential to include planting & harvesting technology innovations such as EC7, EC8, EC9, EC15, EC17 and F24, although there would be some challenges inherent in setting up demonstration sites that are ideal for the innovations, particularly around hard-to-access locations and soft ground.

All other categories of innovation that would have a positive impact on future production of UK sustainable biomass include:

- (EC5 + EC6) Innovations that scale up production of planting materials, e.g.
  - Innovations related to improved rhizome production, storage and transportation
- (EC7, EC8 + EC9) Planting machinery innovations to increase establishment success and productivity, e.g.
  - Planting machinery innovations combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land.
  - Machinery and strategies for planting plug-plants to increase establishment success, widen planting window and reduce environmental impact e.g. biodegradable films (not plastic), automated planting systems
  - Machinery development for automated rhizome planting
- (EC15, EC17 + F24) Innovations in energy crop and forestry harvesting machinery to improve efficiency and access to difficult sites, e.g.
  - Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs
  - Innovations in baling technology
- (EC23) Innovations in storage, e.g. development of optimised storage systems including on-farm storage to maximise feedstock quality and scale-up storage facilities
- (EC18) Increasing knowledge on optimal harvesting and guidance for growers, through research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality, and improved decision support and planning tools at a farm-scale.
- (F3 + F4) Innovations in species selection for SRF and LRF Broadleaved and Coniferous, e.g.
  - Selection of species according to rapid volume growth and good stem form
  - Alternative species selection considering attributes important from a bioenergy perspective such as 'energy growth', the amount of biomass that could be available for bioenergy, carbon stocks, GHG emissions, other environmental impacts, moisture content at harvest.
- (F5 + F6) Provenance choice for LRF and SRF, when plants from a given original seed source (provenance) are grown in a different location
- (F8) Genetic selection for SRF using the selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors
- (F31) Decision support tools and platforms to provide easy to access information on species, provenance and genetic material, tools to assess land suitability

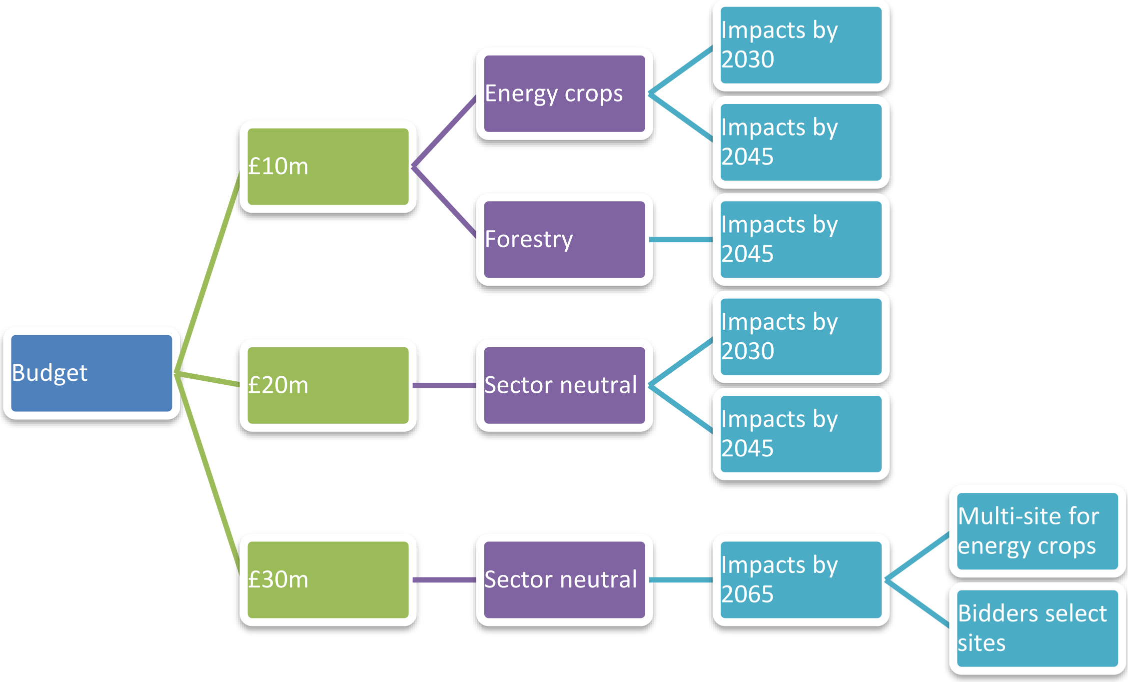
How many projects could be supported?

The £20m budget for energy crops could fund between 10 and 15 projects spread across the range of categories, with estimated project budgets for innovations in the above categories ranging between £500k and £4m (50% funding would equate to grants between £250k and £2m). The impact of recommending a competition with a multi-site demonstration workstream would be fewer energy crop projects funded relative to a targeted competition, due to higher project costs for energy crop innovation projects that are appropriate for demonstration sites. Within a suggested budget of £10m for forestry, an estimated 20-30 individual projects could be funded from the categories above. There is an additional risk at the scale of £30m total funding, that the market struggles to deliver the appropriate number of projects and high quality proposals to utilise the full budget. This risk is addressed to a degree in Section 7 of this report, with recommendations around promotion of the competition and actions to increase the likelihood of good quality applications. Of all the forestry innovation categories, innovations in species selection and decision support tools scored the highest for production potential, so the competition could prioritise funding at least 10 projects in those categories to gain maximum impact.

6.2 Discussion of key sensitivities (variable parameters)

The diagram below demonstrates the key decision routes once the budget approval has been made.

Figure 6-1: Innovation competition decision tree determined by budget selection



It is important to emphasise that all three budget ranges allow for a competition that would positively impact the amount of UK bioenergy production, with multiple options for innovations that could be funded with a high degree of industry interest.

In the decision tree above, there is a common theme of sensitivity around timescale of impacts, which are defined in this feasibility study as demonstrating a measurable increase in sustainable biomass feedstocks. The overarching EIP aim is to accelerate the commercialisation of innovative clean energy technologies and processes into the mid-2020s and 2030s. The successor fund to the EIP, under which a future innovation competition in the area of sustainable biomass would operate, is likely to have updated timeframes in its core aim. As the successor to EIP is assumed to deliver innovation programmes from April 2021 onwards, three impact timescales were considered:

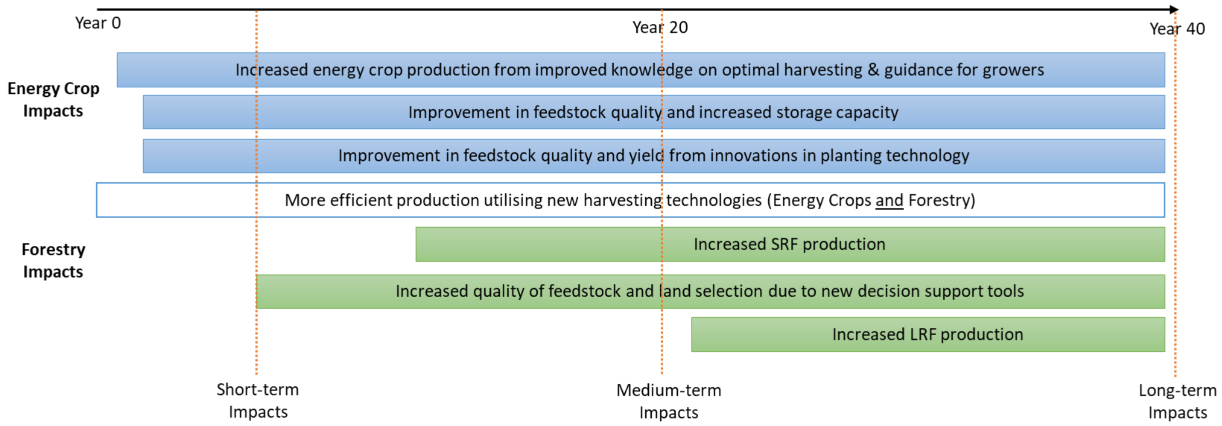
1. Increase in production in the short term (by 2030) – impact within five years of project completion
2. Increase in production in the medium term (by 2045) – impact within 5-20 years
3. Increase in production in the long term (by 2065) – impact within 5-40 years

Stakeholders did not share a strong view on the timescale for impacts, other than to note that some innovations in both energy crops and in forestry would typically lend themselves to long-term impact realisation rather than short-term.

That said, based on the MCA scoring, the majority of innovations were thought to be able to deliver an impact in the short term, allowing for a range of benefits to be realised within five years of project completion. Of the 53 innovations scored, 31 were rated as delivering an impact in the short-term, 12 in the medium- and only 8 in the long-term.

As an illustrative example, innovations have been shown against a 40-year timescale to provide some clarity on the potential effects of selecting different impact timescales for the boundaries of the competition.

Figure 6-2: Example timeline of innovation



What this demonstrates is that for some innovations, the beneficial impact on increased UK production of sustainable biomass can only be realised many years in the future. This is particularly true for impacts on forestry production, although new harvesting technologies would have a positive impact within a very short timeframe. A competition with a short-term impact focus (up to 2030) is more likely to fund projects at a higher TRL level with them becoming commercially available by 2024/25. Even though this would clearly be beneficial to the sector overall, this approach would not accelerate technologies at lower TRLs in the same way.

This does not mean that projects at a lower TRL or those with slow grow patterns (such as SRF and LRF) should be excluded from the future competition simply due to the difficulty in measuring benefits over such long timescales. Projects to implement species and genetic selection can be modularised into stages with clear goals and success factors to allow measurement of progress and likely degree of long-term benefits throughout the intervening years before yield can be recorded. So for example the first stage might be desk based research to identify promising species through the re-evaluation of current information.

Stakeholders consulted at the workshop in November 2019 emphasised that bioenergy can be used for a range of uses and sectors, many of which are searching for low carbon alternatives now, hence innovations that can be delivered in the shortest possible time should have highest importance.

Stakeholders viewed timescale of impact as a critical decision for BEIS to confirm ahead of the final competition design.

6.3 Summary of scenario assessment

The assessment of the 16 funding scenarios shows that any one of the potential parameter combinations would likely improve on the current level of UK production, with varying degrees of successfully achieving the overarching programme-level objectives. The recommended scenarios were:

- Low budget (£10m): B1
- Medium budget (£20m): G
- High budget (£30m): N

Table 6-4: Summary of scenario analysis

Scenario	A1	A2	B1	B2	C	D	E	F	G	H	I	J	K	L	M	N
Budget	L	L	L	L	L	L	M	M	M	M	H	H	H	H	H	H
Sector	Energy crops	Forestry	Energy crops	Forestry	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
Timescale	Short	Short	Medium	Medium	Short	Medium	Short	Short	Medium	Medium	Short	Short	Medium	Medium	Long	Long
Programme type	Targeted	Targeted	Targeted	Targeted	Targeted	Targeted	Targeted	Multi-site	Targeted	Multi-site	Targeted	Multi-site	Targeted	Multi-site	Targeted	Multi-site
Ability to meet objectives																
Increase amount of UK production																
Reduce GHG emissions																
Reduce cost of production																
Improve resilience to future climate change impacts																
Acceleration of innovative technologies																
Likelihood of key risks occurring																
Failure to recruit sufficient applications																
Technology supply chain bottlenecks																
Sites are not sufficient to demonstrate impact																

6.4 Other competition design components not linked to scenarios

The design of the future innovation competition has further components that are not linked directly to the achievement of the technical objectives, but that will play a fundamental part in the likelihood of success.

6.5 Timescale to launch

The budget for the future innovation competition is expected to be approved under the successor to the EIP, starting April 2021 and likely to run for 3 years to March 2024.

At the stakeholder briefing event on the 18th November, BEIS indicated a desire to launch the future innovation competition on a timescale that allows grants to be awarded and projects to prepare for an April 2021 start date, giving maximum time for projects to deliver before March 2024.

A resulting recommended timetable of activities is shown below in Table 6-5.

Table 6-5: Suggested key milestones in launching a future innovation competition

Milestone	Suggested date for achievement
Initial competition announcement	Summer 2020
Competition launch	September 2020
Expressions of Interest (EoIs) submitted	October 2020
Feedback returned on EoIs	November 2020
Full applications submitted	January 2021
Assessments complete	February 2021
Awards issued	February 2021
Grant contracts signed and countersigned	March 2021

An early announcement on the overall objectives, budgets and timescales of the competition, along with information on the standard terms & conditions of the grant contracts is recommended, as this allows potential bidders to begin forming consortia and developing their proposals to align with the key requirements of the competition. Feedback from stakeholders at the 18th November workshop supported this approach, with them suggesting maximum time to prepare for the competition if the grant budget could only start to be spent in April 2021.

The process of submitting and reviewing expressions of interest (being a one to two page summary of the proposed project) has proved useful for bidders in previous innovation competitions, where the risk of committing internal resources to preparing a fully costed high quality bid has to be balanced against the likelihood of success and other competing demands for time.

Finally, a four month application process typically allows bidders time to be supported by the funder to deliver good quality proposals though activities such as Frequently Asked Questions, webinars on setting up consortia or commercialisation plans (where relevant), and even offering reviews of draft applications. Assessment processes can be condensed into four to six weeks depending on the number of applications, culminating in grant offers being made within six to eight weeks of the application deadline.

It is also important to note that promotion and communication regarding the competition will need significant effort to reach all potential applicants. One of the key challenges of the last decade of innovation funding in central Government has been a movement away from long-term programmes towards 'one-off' competitions, which prevents the build-up of a communicable programme of investment. An ideal innovation and deployment programme would have clear visibility of phased funding plans over a five to ten year timescale, with supporting tools, guidance, websites, events, trained staff and branding all adding to the likelihood that landholders and SMEs that are not engaged with the latest innovations start to enter the market. Without that surety of future funding being in place, a more significant effort will need to be made upfront to promote and engage landowners in the upcoming single-round competition so that the opportunity to apply for funding is maximised.

6.6 State Aid submission

This Section reviews the existing State Aid Regulations which determine the types and amounts of Government funding that are permissible within the European market in order to identify the most appropriate category of aid for a potential new competition.

Regarding the use of State Aid routes for grant funding, much depends on the timescale for development and launch of a scheme. Longer term programmes (such as those run by the Carbon Trust, Innovate UK and ETI) have all applied for a specific full State Aid exemption using the full notification procedure which allows for maximum control over the design of the scheme, but requires in-depth justification of the requirement for market intervention. Within UK Government Departments, BEIS, Defra and DfT have all used State Aid General Block Exemption Regulations to deliver grant funding schemes with a shorter lead-time.

The European Commission's State Aid regulation is designed to prevent Government funding from causing unfair competitive advantages within a given market. In designing a funding scheme to support demonstration projects, there are a number of routes available that will comply with State Aid legislation, including block exemptions and a full notification procedure, which is known as an individual exemption.

General Block Exemption Regulations (GBERs) provide a list of specific conditions under which Member States may launch a funding scheme without being required to complete the full notification procedure. Provided the block exemption conditions are met, the programme manager may simply notify the Commission via a retrospective transparency notice. In the event of a very large individual award being made, a notification must still be made to the Commission – even when the scheme under which the award has been made satisfies all of the requirements of GBER.

If it is not possible to comply with all the conditions of a block exemption, the program manager must apply for an individual exemption using the full notification procedure which can take at least three to six months.

The majority of innovation competitions under the EIP have been funded via the GBERs. In particular, previous competitions have utilised Article 25 (2c) of the GBER for funding Research & Development projects under the category of 'experimental development'. This allows a grant intensity of 25% with additional uplifts allowing a maximum funding intensity of 60%. The table below provides an overview of all exemptions under the GBER that could potentially be relevant to projects funded by a new competition.

Article 41 (investment aid for the promotion of energy from renewables) is a relevant exemption as it contains specific provisions for biofuel production from sustainable feedstocks and covers all aspects of energy from bioenergy. An individual project could rely upon any combination of the exemptions, subject to the accumulation rules and would be responsible for demonstrating they comply with the GBER (some existing EIP application form templates contain guidance to assist bidders with this).

Table 6-6: State Aid exemption options for a new innovation competition

Article and title	Scope & Eligible Costs	Maximum aid intensity	Aid intensity uplifts	Maximum Threshold
25 – Aid for research and development projects.	(b) **experimental development** (meaning acquiring, combining, shaping and using existing scientific, technological, business and other relevant knowledge and skills with the aim of developing new or improved products, processes or services. This may include development of commercially usable prototypes);	Experimental development: 25%	+ 10% for medium-sized enterprises; + 20% for small enterprises. + 15% if one of the following conditions apply: - if the project involves effective collaboration (see Art 25(6)(b)(i) for more details); or - if the results are widely disseminated (see Art 25(6)(b)(ii) for more details)	Experimental research: 15m Euros per recipient, per project
Article 41 – investment aid for the promotion of energy from renewables	Eligible Costs – the extra investment costs to promote the production of energy from renewable source. Restrictions apply regarding biofuels which must use sustainable feedstocks that are non-food-based.	Aid intensity may be set by the funder subject to the process being a competitive application	+ 20% for small undertakings; + 10% for medium-sized undertakings. + 15% for Assisted Area (a); 5% for Assisted Area (c).	15m Euros per recipient, per project.

Accumulation rules

Aid granted under one GBER exemption may be accumulated with aid under a different GBER exemption in relation to the same identifiable Eligible Costs, partly or fully overlapping, only if such accumulation does not result in exceeding the highest aid intensity or aid amount applicable. This multiple GBER approach is taken in current funding schemes such as the Scottish Government's Local Energy Challenge Fund, which allows a large range of different project types to utilise the eligible technologies and costs for multiple Articles to determine the best 'fit' for their projects.

At this stage of the feasibility project, either exemption would be applicable to the future innovation competition, although Article 41 would pre-suppose the biomass has a bioenergy end-use.

Under State Aid regulations, the competition would be open to applications from businesses, research institutions, land owners and Local Authorities. Funding could broadly be used for all material, equipment and staff costs necessary to complete the innovation project. Funding could not be used for protection of Intellectual Property Rights, generating profit, recoverable VAT, interest payments or Hire Purchase agreements.

6.7 Required documentation

A future innovation competition will require the following documentation to be drafted, reviewed, and approved for issue via the BEIS webpages:

- Guidance document, including a copy of the Grant Funding Agreement terms & conditions
- Application form, to include work plan requirements, risk assessment and project partner details
    - Appendix to contain BEIS Finance Form
- Monthly/quarterly report template
- Final report template

6.8 Application process

As detailed in section 5.1 a two-stage application process is recommended to allow prospective bidders to focus their efforts on the applications most likely to be funded.

- At Stage 1 of the application process, prospective bidders would submit 2-page proposals outlining their project, its key tasks and timescales, the preliminary budget, and the project partners. The proposals would be assessed and projects deemed to be non-compliant or at a significant weakness with the overarching competition objectives or that have been poorly prepared would be removed from the process.
- At Stage 2 of the application process, prospective bidders from Stage 1 would submit detailed proposals for the full project. Prospective bidders must pass Stage 1 to be eligible to apply for Stage 2.

  Further to this, stakeholder feedback indicated that there would be a significant barrier to applications for 'straightforward' machinery innovation in comparison to more complex innovations, regarding the level of detail required in the application form. Stakeholder, particularly those who were SMEs, stated they would be unlikely to apply for funding for projects in the region of £50k - £200k if the application form was overly burdensome. A recommended approach to resolve this issue would be to make a short-form application form available for projects applying for less than £100k of grant, which would help to streamline the assessment of more complex projects and reduce the burden of application preparation for SMEs. This approach has been utilised successfully on other competitions previously, such as the bioenergy capital grants scheme (run by DECC prior to the introduction of the Renewable Heat Incentive).

Both Stage 1 and Stage 2 applications should be assessed via defined eligibility and evaluation criteria, subject to review by a Selection Panel, and final funding recommendations to Ministers should be made by a Project Board and/or Investment Panel.

At the point of grant award, notification letters would be drafted and issued to all applicants informing them of the outcome of the assessment process, including feedback gathered from the assessors. Grant Funding Agreements, including a Grant Offer Letter and Payment Milestones would then be drafted and issued to successful applicants. In parallel, BEIS Finance typically carry out financial due diligence and will highlight any additional requirements to be included in the Grant Offer Letter.

7 Industry appetite for a future innovation competition

7.1 Introduction

Throughout the feasibility study, industry appetite for a future innovation competition was tested at multiple points with stakeholders, including through two stakeholder workshops.

All identified innovations were rated for industry appetite during the MCA, and barriers to application were explored at both workshops. These ratings showed high industry interest for the majority of innovations: of the 53 innovations considered, stakeholders suggested interest would be 'high' in 27, 'medium' in 9, 'low' in 15 and there would be no interest in two. Of the top 20 innovations scored in terms of potential impact on scaling up of production, industry interest was considered 'high' in 16 and 'medium' in four.

The following Section details the major feedback from stakeholders for an innovation competition, gathered throughout the study.

7.2 Key drivers for potential future applicants

Overall, the key drivers for potential future applicants to an innovation competition aimed at increasing the amount of UK production of sustainable biomass are:

- To further develop their own business or innovation product,
- To scale up bioenergy production,
- To identify business models that will enable bioenergy feedstock growth and the extent to which business models and innovations will address challenges in supply chains,
- To understand how land managers will respond to proposed innovation activities and which innovation activities are most likely to overcome perceived barriers.

7.3 Key barriers perceived for potential future applicants

The key barriers that were perceived for potential future applicants to the innovation competition (linked to the competition itself) were:

- Not having clear information regarding the innovation competition with suitable notice before the bidding window

This has been addressed by recommending an early release of key information ahead of the competition launch, to enable partnering conversations to begin.

- Insufficient length of bid window

Initial feedback reflected that a two-month window was insufficient, which has been addressed partly by recommending a two-stage process for application, therefore reducing the time that prospective bidders initially commit to putting an application together. Application windows of 10-12 weeks have also been recommended for the full application.

- Lack of an initial steer on bid from evaluation panel and/or inability to discuss bids with the assessor/funder.

This is a common issue across all innovation competitions. Recommendations for addressing this barrier include setting up advice 'sessions' which are open for prospective bidders to attend and ask questions. Adding an EOI phase also gives prospective bidders early feedback on their project and its overall fit with the competition objectives.

- Lack of awareness due to insufficient advertising of competition through specific channels

This was flagged as a risk in all scenarios, particularly the higher-budget scenarios, as significant effort will need to be made to ensure the competition is promoted to potential applicants. Recommendations to mitigate this risk include early engagement to maximise the timescale for potential bidders to understand the competition requirements (as per Section 6.5 recommendations) and to build networks of contacts through engaging national and regional trade bodies such as the NFU and regional woodfuel supply networks and trade publications such as Farmers Weekly, including running promotions, adverts and events. The timing of these communications will be crucial as potential bidders are unlikely to give the competition much attention over the summer harvest months.

- Inability for single entity to submit multiple bids

This has been addressed with a recommendation to allow multiple bids from single lead organisations, reflecting the need for projects to take place simultaneously to improve the supply chain.

- Clarity on continuity or follow-up for projects with long-term objectives that have been modularised (i.e. separated into smaller stages) to be delivered within the funding window (i.e. by March 2024)

Again, another common challenge for innovation competitions where benefits will not be realised during the lifetime of the funding. Recommendation to set up a longer-term evaluation and reporting framework that extends past the end of the spending review if possible.

- Potential lack of recognition of the potential achievements of tackling longer-term issues against more visible achievements of shorter-term projects in the evaluation criteria

Consideration has been given to this issue, and the high budget scenario recommendation is to include innovations with a long-term impact due to their high potential to improve long term resilience to the impacts of climate change.

- The complexity of the bid process, including the volume of information required and resource needed to write the bid

A recommendation has been made to streamline the bidding process for lower value proposals, addressing some of the barriers that landowners and SMEs face in competing for funding with more experienced organisations.

Glossary

EC	Energy Crops
AD	Anaerobic digestion
CCF	Continuous Cover Forestry
CEO	Chief Executive Officer
EAMU	Extensions of Authorisation for Minor Use
ETI	Energy Technologies Institute
GB	Great Britain
GHG	Greenhouse gas
ha	hectare
LiDAR	Light Direction and Ranging
LRF	Long Rotation Forestry (conventional forestry)
MWh	MegaWatt hour
odt	Oven dry tonne
SRC	Short rotation coppice
SRC(p)	Short rotation coppice (poplar)
SRC(w)	Short rotation coppice (willow)
SRF	Short Rotation Forestry
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UKFS	UK Forestry Standard

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Appendices

Appendix 1: Production Cost Data

Appendix 2: Multicriteria Assessment Scores and Ranking of Innovations

Appendix 1 – Production Cost Data

A1 Production Cost Data

A1.1 Costs for perennial energy crops

The costs reported from a number of literature sources for SRC willow are shown in Table A1.1 and those used for estimation of costs in this study in Table A1.2. For *Miscanthus,* costs identified in the literature review are given in Table A1.3 and those used in this study in Table A1.4. A full discussion of the costs is given in the supporting document (Ricardo, 2020).

Table A1-1 Reported SRC Willow production costs (converted to 2019 prices)[a]

Activities		Units	Source and year of study (see details below the table)					
			[1] 2001	**[2] 2014**	**[3] 2011**	**[4] 2013**	**[5] 2016**	**[6] 2016**
Pre-planting/ land preparation	Professional costs	£/ha			198		94	
	Drainage, liming	£/ha					169	
	Ploughing / discing	£/ha	27		91	98	51	61
	Power-harrow	£/ha				64		51
	Miscellaneous	£/ha			29			91
	Herbicide	£/ha	65		58	248	55	
	Fertiliser	£/ha	58					
	Pest protection (rabbit fencing)	£/ha						238
	Total pre-planting	**£/ha**	**150**		**375**	**410**	**370**	**441**
Planting	Planting density	plants/ha						15,000
	Plant material	£/ha	2,301		1,414	1,577	1,247	969
	Planting	£/ha	262		138	136		280
	Fertiliser	£/ha	30		70			
	Herbicide	£/ha	22		91		153	178
	Total planting	**£/ha**	**2,614**	**2,276**	**1,713**	**1,712**	**1,399**	**1,428**
Post-planting	Herbicide / weed / spray	£/ha	50		29		54	178
	Gapping up	£/ha					14	
	Cutback / mowing	£/ha	101		41		49	49
	Total post-planting	**£/ha**	**151**	**0**	**70**	**0**	**117**	**227**
Harvesting	Harvesting	£/ha	351	165	445	522	596	520
	Handling / storage	£/ha	58					207
	Fertiliser	£/ha	91	32	144			
	Weeding	£/ha	50			72		
	Total harvesting costs	**£/ha**	**549**	**196**	**589**	**595**	**596**	**727**
Other annual costs	Miscellaneous harvesting costs	£/ha/year					16	
	Professional costs & management	£/ha/year		111	10	94		
Reversion	Reversion	£/ha	n/a	639	610	60	271	n/a

Sources:

[1] (DEFRA, 2001) [2] (Alexander, et al., 2014) [3] (Buchholz & Volk, 2011) [4] (Schweier & Becker, 2013) [5] (Energy Technologies Institute, 2016) [6] (Forest Research/Uniper, 2016b)

Notes:

[a] Blank cells indicate that data is not provided by original source: in some cases it may have been aggregated with another figure; in others it may not have been considered. Costs have been converted from the year of the original study using UK GDP deflators[7], and for US costs in [2] using an exchange rate of £1=US$1.6349 in 2003.

[7] GDP deflator taken from June 2019 quarterly national accounts (https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-june-2019-quarterly-national-accounts). Dollar exchange rate from Office for national Statistics Average Sterling Exchange Rate data set at https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/timeseries/auss/mret

Table A1.2: Assumptions for cost modelling of SRC (Figures in 2019£)

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Professional costs (e.g. EIA, agronomy)	Environmental Impact Assessment required under energy crops scheme. Agronomist advice often needed by farmers.	UK specific costs. Unclear whether included in many literature sources.	Figure available for EIA for SRC available from Brackenthwaite farm data (ETI) (Energy Technologies Institute, 2016). An EIA is needed typically if in receipt of a planting grant. Assumed an EIA is needed in base case & high case. Agronomy advice figure provided by expert advisor. Base and high cases assume one visit by agronomist at start and at every harvest; low case assumes no advice sought from agronomist.	Low, if only carried out once and/or infrequently
Soil sampling	Required to understand fertilisation needs	Little data shown in literature for this activity - may be included in with other costs in some sources but lack of transparency prevents confirmation. Figure of £6/ha (£6.17 adjusted to 2019£) available for SRC at Brackenthwaite farm (Energy Technologies Institute, 2016).	Figure of £6.17/ha used throughout. For all cases, a soil sample is shown every 5 years.	Low - low cost, carried out infrequently

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Clearance and ploughing	Weed killer likely to be applied and land ploughed using usual ploughing equipment. Easier & cheaper to do if land previously in agricultural use. If previously marginal land, then costs will be higher because of stones and past root material. May require two visits if so.	Costs in literature variable from £27-£98/ha giving an average of £77/ha. Low figure of £27 disregarded as old data and not reasonable after expert review.	Figure of £85/ha used for base case (expert reviewer considers this figure appropriate)- £93/ha for high case (+10%) and £78/ha for low case (-10%). Consistent with inspection of data from literature and with *Miscanthus* findings. Sensitivity analysis includes combined ploughing/harrowing/clearing costs.	Low - only carried out once.
Total herbicide + application by farmer	Total herbicide (glyphosate) is regularly added during a plantation's life both to the field for clearance purposes in year -1 and around the growing crops in later years to keep weeds in control. Weeds can outperform the growing *Miscanthus* and hence have to be controlled. Herbicide can be applied by the farmer or a contractor.	The average costs for herbicide application at two different points in time were £64/ha and £78/ha. High figure of £270/ha disregarded - may include additional elements over and above herbicide application.	Expert review considered this high. Cost of £7-8/l at 5l/ha equates to £40/l for herbicide product plus £10/ha for farmer to apply or £12.50/ha for a contractor to apply. Assumed £50/ha applied once for the base case; £52.50 applied once for the high case; £50/ha applied once for the low case.	Low - as only one application (but if not done correctly can impact yields which has a high impact)
Power-harrow	Used to prepare the soil to the right consistency for planting the willow rods.	Two figures of £51 and £64/ha (2019£ – see Table) quoted in literature giving an average of £57/ha - £60 considered an appropriate figure by expert reviewer.	Figures of £60/ha used for base case; £66/ha used for high case (+10%); £54/ha used for low case (-10%). Sensitivity analysis includes combined ploughing/harrowing/clearing costs	Low - only carried out once.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Land preparation (miscellaneous)	Unstated cost elements from literature review. Addresses risk cost for potential additional costs arising out of any challenges during land preparation.	Literature review shows data ranging from £29/ha to £91/ha with an average of £60/ha.	For the base case, £60/ha has been used; for the high case, £91/ha has been used; for the low case £30/ha been used.	Low - only added once and low in value.
Pest control incl. rabbit fencing	Used to prevent rabbits accessing the growing plant shoots. Expensive. Typically not installed unless there is a high risk of rabbit damage. Other herbivores can also be an issue. Risk of fencing in rabbits sometimes not considered.	Literature data shows only one figure of £238/ha (2019£ – see Table).	Expert review considered a cost of £300 as used for *Miscanthus* for fencing appropriate. But, only applied to the base and high cases.	Medium - can have an impact if very expensive.
Plant material	Consists of cost of plant material (rods) from supplier plus transport from supplier to farm.	Costs in literature range from £969/ha to £1,577/ha (2019£ – see Table). A high figure of £2,301 is from an old source and may include additional cost elements so has been disregarded. Average of £1,236.	Expert review indicated a cost of £900-950/ha for the plant material plus around £75 for transport - a total of £975-1,025 which agrees reasonably well with the data from the literature review. Indicates potential cost reductions could have taken place over the past few years. For the base case a figure of £1,100 has been used; in the high case £1,250 has been used and in the low case £975 has been used. Sensitivity analysis examines the impact of planting cost between £1,050 and £1,950/ha.	Medium - while this cost forms the major part of the whole establishment costs, they only happen once.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Planting	Consists of cost of plant and labour to plant the willow rods in the field.	Costs in the literature range from £136 to £280/ha - average £253/ha (2019£ – see Table).	Expert review considered these figures low. Experts recommended a cost of between £400 and £450/ha. Figures of £400/ha are used in the base and low cases. £450/ha is used in the high case.	Medium - while this cost forms the major part of the whole establishment costs, they only happen once.
Fertiliser + application by farmer	Fertiliser will be applied either by the farmer or a contractor after planting in and around the plants. Fertiliser could be a purchased product or sewage sludge (if permitted) which comes at zero cost (or perhaps even negative cost).	Some sources show fertiliser use; some do not. Where they do, figures are variable and are at different points in time. One reason for the variability may be due to use of sewage sludge (free or negative cost but not always possible to use) vs purchased product.	Due to variability in data sources, data from consultation used. For the base case and high case, purchased product (£25/ha) is shown used, applied by the farmer in the base case (£10/ha) and by a contractor in the high case (£12.50/ha). In the low case, sewage sludge at £0/ha is assumed, applied by the farmer (£10/ha). Fertiliser is shown as being applied in the first year (year -1), the year of planting (year 0) and in each harvest year.	Medium - this is a high frequency cost but is low cost.
Weed/spray	At the end of third year (year 1) when the leaves have fallen, the farmer will apply herbicide and cut back the crop to encourage the plant to grow more stems.	An average of £82/ha (consistent with Miscanthus data) was considered appropriate by the expert review (Table).	For the base case, £82/ha has been used in year 1 (3rd year of the plantation life and at every harvest). For the high case, £90/ha (+10%) has been used and for the low case, £74/ha (-10%).	Medium - low cost but carried out frequently

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Gapping up	In the third year (year 1), the farmer will fill any gaps in the crop with new, larger size (e.g. 60 cm long) willow rods which can compete with the already established plants which have just been cut back	Literature shows only one figure of £14/ha (Brackenthwaite farm in (Energy Technologies Institute, 2016)) (2019£ – see Table).	Expert reviewer considers £15/ha appropriate. £15/ha has been used for the base case; £17/ha for the high case (+10%); £13/ha (-10%) for the low case.	Low - low cost plus only carried out once.
Cutback/mowing	In the third year (year 1), the farmer will cut the emerging willow shoots to encourage more shoots per plant.	Literature data shows a range of £41-£49/ha (a high figure of £101/ha is from an old source and may include some additional elements and so has been disregarded) (2019£ – see Table).	A figure of £50/ha has been used in the base case; £55/ha in the high case (+10%); £45/ha in the low case (-10%).	Low - low cost plus only carried out once.
Harvesting / handling / storage	Harvesting typically carried out using a modified forage harvester which cuts the willow and cuts it into short lengths (billets) which are blown out of the harvester into an accompanying trailer.	Literature data averages £542/ha with a maximum of £729/ha and a minimum of £196/ha. Figures for handling / storage were considered too low by the expert review at an average of £132/ha (lack of data). Expert review recommended using £225/ha.	£725/ha used for the base case (£500+£225); £750/ha for the high case; £625 for the low case. The low case figure is more reflective of the figure recorded for Brackenthwaite farm (Energy Technologies Institute, 2016).	High - high frequency operations have a high impact on cost variability. Sensitivity analysis includes harvesting cost.
Miscellaneous costs	Represents costs in literature for other cost elements plus some element of risk.	Brackenthwaite farm (Energy Technologies Institute, 2016) shows a cost of £16/ha for miscellaneous (2019£ – see Table).	A figure of £20/ha is included for the base case; £30 in the high case; £10 in the low case	Low - low cost element.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Reversion	At the end of a plantation's life, the field is ploughed and weed killer is applied to allow the farmer to use the field for another purpose.	Literature review data ranges from £271/ha (Brackenthwaite farm) to £639/ha. A low figure of £60has been disregarded as unrepresentative of the range of tasks that are carried out during reversion.	For the base and low cases, £300/ha has been used (reflective of Brackenthwaite farm figure). For the high case, £450 has been used, reflective of the average of the literature review data.	Low - this is a one-time only cost
Moisture content at harvest	Moisture content of willow SRC at harvest is typically high at 55-60% - higher moisture contents are challenging for efficient combustion / gasification. For smaller applications, this is too high. Some larger applications may be able to use fuel with a high moisture content.	Brackenthwaite farm (Energy Technologies Institute, 2016)shows a figure of 57.5%.	57.5% moisture content is used to calculate the dry yield (odt/ha) from which the cost/odt has been calculated.	-
Yield	Yield can be quoted in various ways - oven dried tonnes/ha (odt/ha), fresh tonnes/ha and either per year or on a plantation life average. It is not always clear in the literature which is quoted.	Data from Brackenthwaite farm (Energy Technologies Institute, 2016) (in fresh tonnes/ha) has been used for all cases. Expert review considers these figures appropriate (Energy Technologies Institute, 2016).	Yield starts at 25 fresh tonnes/ha rising to a maximum of 32 fresh tonnes/ha/harvest. This results in a total production of 205 tonnes and an average annual yield of 9 odt/ha/year.	High - this has a direct impact on all costs making up the cost/tonne metric.

Table A1.3: Reported *Miscanthus* production costs (converted to 2019 prices)[a]

Activities		Units	Source and year (see details below the table)								
			[1] 2001	[2][b] 2003	[3][c] 2010	[4][d] 2011	[5] 2015	[6] 2015	[7] 2016	[8][e] 2016	[9] 2018
Site preparation	Clearance & ploughing	£/ha	106	28		55	44	59	90	329	85
	Herbicide	£/ha	97	21		110	50	43			
	Miscellaneous / overheads	£/ha	131	97	0	100	0	0	55		
	Total preparation	***£/ha***	***334***	***146***	***0***	***265***	***94***	***102***	***146***	***329***	***85***
Planting	Power-harrow	£/ha					29	43			
	Pest control	£/ha					122	476	266		
	Rhizomes density	No./ha	n/a			20,000	n/a	n/a			
	Rhizomes	£/ha	1,438	281		1,489	1,978	1,626	1,328	1,381	1,785
	Planting	£/ha	100	61		387				212	
	Fertiliser	£/ha	34	45	0		5				22
	Herbicide	£/ha	92				50	43	21	202	
	Misc/overheads	£/ha	107	41		100	0	0	74	106	
	Total planting	***£/ha***	***1,771***	***429***	***2,276***	***1,976***	***2,185***	***2,189***	***1,689***	***1,901***	***1,807***
Harvesting	Mowing / cutting	£/ha/year	23	34		229	65	65	80		83
	Baling	£/ha/year	125	194			265	258	244		186
	Baling	£/fresh tonne					10	11	14		14
	Loading	£/ha/harvest	14	92			22				53
	Drying	£/ha/year					0	39			
	Misc/overheads	£/ha/year	75	82	305	143	11	16	0		0
	Total harvesting	*£/ha/year*	*238*	*403*	*305*	*9*	*362*	*378*	*323*	*n/a*	*321*
Reversion	Reversion costs	£/ha			127	115	108	108	106		102

Sources: [1] (DEFRA, 2001); [2] (Khanna, et al., 2008) (converted from US$); [3] (Alexander, et al., 2014); [4] (Wang, et al., 2012); [5] Data for Abbey Farm in (Energy Technologies Institute, 2016); [6] Data for Friars Farm in (Energy Technologies Institute, 2016); [7] (Forest Research/Uniper, 2016b) & (Croxton, 2019); [8] (Hastings, et al., 2017); [9] Average figures from (Redman, 2018)

Notes:

[a] Blank cells indicate that data is not provided by original source: in some cases it may have been aggregated with another figure; in others it may not have been considered. Costs have been converted from the year of the original study using UK GDP deflators[8], and for US costs in [2[using an exchange rate of £1=US$1.6349 in 2003.

[b] Rhizome cost is low because only 10,000/ha are planted at a cost of 3.4 cent/rhizome (2p per rhizome (in 2019£) compared to typical planting rates of 25,000/ha at a cost of 5-10p per rhizome.in the UK.

[c] Alexander Moran et al group the costs of land preparation in with planting costs; a single figure for both of these elements is reported in the total planting row;

[d] Wang et al (2012) give a cost of £38 for bale storage which is included in the miscellaneous costs

[e] Hastings et al (2017) do not give a breakdown of harvesting costs and the year for cost data is unclear but is assumed to be 2016

[8] GDP deflator taken from June 2019 quarterly national accounts (https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-june-2019-quarterly-national-accounts). Dollar exchange rate from Office for national Statistics Average Sterling Exchange Rate data set at https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/timeseries/auss/mret

Table A1.4 Background and rationale to *Miscanthus* data (Figures in 2019£)

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
Professional costs (e.g. EIA, agronomy)	Environmental Impact Assessment required under energy crops scheme. Agronomist advice often needed by farmers.	UK specific costs. Unclear whether included in literature sources.	Figure available for EIA for SRC used for *Miscanthus* following expert advisor advice since an EIA is needed if in receipt of a planting grant (Table A1.3). Assumed an EIA is needed in base case & high case. Agronomy advice figure provided by consultee. Base case assumes one visit by agronomist; high case assumes regular agronomist visits at harvest; low case assumes no advice sought from agronomist.	Low, if only carried out once and/or infrequently and is low cost.
Soil sampling	Required to understand fertilisation needs	Figure of £6/ha available for SRC at Brackenthwaite farm (Energy Technologies Institute, 2016). Unclear whether included in many sources.	Figure of £6.17/ha adjusted to 2019£ used throughout. For all cases, a sum is added at the start and at every harvest.	Low - low cost
Clearance and ploughing	Weed killer likely to be applied and land ploughed using usual ploughing equipment. Easier & cheaper to do if land previously in agricultural use. If previously marginal land, then costs will be higher because of stones and past root material. May require two visits if so.	Costs in literature variable from £28-329/ha giving an average of £99/ha. Expert advice is to use same figure as for SRC as same activity.	Expert's advice was that the figure for SRC was appropriate and to use that (£85/ha) - £85/ha used for base case, £93/ha for high case (+10%), £78/ha for low case (-10%). Sensitivity analysis includes combined ploughing/harrowing/clearing costs.	Low - only carried out once.
Power-harrow	Used to prepare the soil to a depth of about 15 cm to be of the right consistency for planting the rhizomes.	Not quoted widely in the literature but is a typical preparation operation. Two figures of £29 and £43/ha quoted in ETI report for Abbey and Friars farms (Energy Technologies Institute, 2016).	Literature data for *Miscanthus* considered low by expert reviewer. Figures of £60/ha used for base and high cases (taken from SRC data set).	Low - only carried out once.

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
Total herbicide / insecticide + application by farmer	A Total herbicide (glyphosate) will be used to destroy weeds and other plants - it can be applied by the farmer or a contractor. Weeds can outcompete the growing crop impacting yields. Insecticide may be added to the weed killer and sprayed at the same time if insect control is thought necessary.	Most sources showed a cost, ranging from £21-110/ha with an average of £64 (see Table A1.3)	Expert review considered the average (but not the range) reflective of actual costs. Cost of £7-8/L at 5L/ha equates to £40/L for herbicide product plus £8/L for insecticide plus £10/ha for farmer to apply or £12.50/ha for a contractor to apply. Assumed £58/ha for the base case; £60.50 for the high case; £50/ha for the low case.	Low - as only one application (but if not done correctly can impact yields which has a high impact)
Miscellaneous establishment costs	This covers additional costs including risk costs (e.g. in case of more fuel needed if ploughing is harder than expected).	Quoted figures range from £0/ha (ETI data) to £107/ha (see Table A1.3)	For the base case, a figure of £50 was agreed with the expert reviewer for the base case. Increased to £125 (reflective of higher end of literature figures) for the high case and set to zero for the low case representing no additional establishment issues or costs arising in the low case.	Low - only applied once.
Pest control incl. rabbit fencing	Used to prevent rabbits accessing the growing plant shoots. Expensive. Typically not installed unless there is a high risk of rabbit damage. Other herbivores can also be an issue. Risk of fencing in rabbits sometimes not considered.	Literature data varies from £122 to £476/ha (see Table A1.3). Not all literature sources show a cost for rabbit fencing.	Expert review considered a cost of £300 for fencing appropriate. But, only applied to the high case.	Medium - can have an impact if very expensive.
Rhizomes, planting, rolling	Consists of cost of plant material, transport, planting using machine and labour (often done by contractor), and follow-up rolling of plantation. Planting costs are the major proportion of total establishment costs.	Costs in literature range from £1,328 up to £1,978/ha (see Table A1.3). Costs have progressively reduced over time.	For the base case a figure of £1,750 has been used (reflective of the higher costs shown in the ETI two farms); in the high case £2,000 has been used and in the low case £1,350 has been used. Sensitivity analysis on base case examines the impact of planting cost down to £1,225.	Medium - while these costs form the major part of the whole establishment costs, they only happen once.

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
Fertiliser + application	Fertiliser will be applied either by the farmer or a contractor after planting in and around the plants. Fertiliser could be a purchased product or sewage sludge (if permitted) which comes at zero cost (or perhaps even negative cost).	Some sources show fertiliser use; some do not. Where they do, figures are variable from £0 to £45 – older data shows higher figures than newer data(see Table A1.3). One reason will be due to use of sewage sludge (free or negative cost but not always possible to use) vs purchased product.	Due to variability in data sources, data from consultation used. For the base case and high case, purchased product (£25/ha) is shown used, applied by the farmer in the base case (£10/ha) and by a contractor in the high case (£12.50/ha). In the low case, sewage sludge at £0/ha is assumed, applied by the farmer (£10/ha).	Medium - fertiliser may be used every few years. Any higher frequency costs will have a higher impact on cost of production.
Total herbicide + application	Total herbicide is added in the second year and possibly also the third year of the plantation's life (years 0 and 1) to control weeds which can outperform the growing *Miscanthus* and hence have an impact on yields.	Lack of data provided in literature for herbicide application in second and possibly third years. Consultation highlighted the need for post planting application.	As above, expert review considered costs from literature review. Same costs as used in year -1 used. i.e. Assumed £58/ha for the base case; £60.50 for the high case; £50/ha for the low case.	Low - low cost, one or perhaps two applications only. But, if weeds allowed to grow, can have a high impact because of impact on yields.
Weed/spray	At the end of second year (year 0) when the leaves have fallen, the farmer will apply herbicide and cut back	An average from the literature data of £82/ha was considered appropriate by the expert review (see Table A1.3).	For the base case, £82/ha has been used in year 0 (2nd year of the plantation life). For the high case, £90/ha (+10%) has been used and for the low case, £74/ha (-10%).	Low - low cost plus only carried out once.
Mowing / cutting	Typically carried out using a modified forage harvester which cuts the *Miscanthus* stems ready for baling into Heston bales.	Literature data varies from £23 to £229/ha (see Table A1.3)These lower and upper figures were discounted as too low and too high in the expert review. Averaging the remaining numbers which ranged from £65-£83/ha gave an average of £73/ha.	Except in year one (all cases), £75/ha used for the base case; £80 for the high case; £70 for the low case. Mowing/cutting is examined in the sensitivity. £30 used in all cases for year 1 given that the plants will be smaller.	High - high frequency operations have a high impact on cost variability

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
Baling	Baling is carried out following cutting. Heston bales of 500-600kg are typical.	Baling costs of £10-14 /tonne with an average of £12/tonne are shown in the literature (see Table A1.3). Expert review considered these figures appropriate.	£12/fresh tonne used for the base case, £15/fresh tonne used for the high case and £10/fresh tonne for the low case. Cost per harvest has been calculated using the fresh tonnes/ha yield.	High - high frequency operations have a high impact on cost variability
Loading, stacking, storage	Handling of product post baling.	Literature data shows this cost as a £/ha/harvest ranging from £14-£53/ha with the high figure removed as it is unclear what it includes for the high number (see Table A1.3). This works out at about £4/tonne. Expert reviewers said that loading is typically costed by the tonne at around £1.50-£2/tonne.	£2/tonne has been used for the base case and £1.50/tonne for the low case. £4/tonne (using the literature data average) has been used for the high case. Cost per harvest has been calculated using the yield.	Medium to high - this is a high frequency cost but forms a small part of the total harvest cost.
Reversion	At the end of a plantation's life, the field is ploughed and weed killer is applied so that the farmer can use the field for another purpose.	Literature review data is consistent showing a cost of £102-127 with an average of £111 (see Table A1.3).	A cost of £85/ha consistent with ploughing cost above plus £40/ha for herbicide and either £10/ha (farmer application) or £12.50/ha (contractor application) has been applied for consistency with figures above. i.e. £135-137.50.	Low - this is a low and one time only cost
Yield	Yield can be quoted in various ways - oven dried tonnes/ha (odt/ha), fresh tonnes/ha and either per year or on a plantation life average. It is not always clear in the literature which is quoted.	ETI data for Abbey and Friars farms (Energy Technologies Institute, 2016) have been used to provide annual fresh tonne yields across each of the cases (Energy Technologies Institute, 2016) - expert reviewer considers these to be an appropriate model.	The same yields have been used in all three cases. The sensitivity analysis includes yield. The yields used result in a total plantation life production of 293 fresh tonnes.	High - this has a direct impact on all costs making up the cost/tonne metric.

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
Cost per tonne			Cost per tonne is given as real cost per fresh tonne (based on a total real costs for the whole plantation divided by 293 fresh tonnes); cost per odt (based on a total real costs divided by total tonnes produced at a yield of 10.6 odt/ha (Wang, et al., 2012). Discounted (at 5%) costs per fresh tonne and per odt are also provided.	

A1.2 Costs for forestry

Table A1.5: Typical costs for LRF establishment and harvesting (£2019)

	Unit	LRF Coniferous Lowland	LRF Coniferous Upland	LRF Broadleaved
Ground preparation				
Deer fencing	£/ha	£255		£710
Draining	£/ha	£40	£75	£40
Cultivation	£/ha	£220	£390	£150
Total ground preparation	***£/ha***	***£515***	***£465***	***£900***
Planting				
Plant supply	*£/ha*	£650	£600	£825
Planting, restock	£/ha	£200	£200	£220
Planting, new	£/ha			
Beat up, labour and plants	£/ha	£340	£200	£345
Total planting	***£/ha***	***£1,190***	***£1,000***	***£1,390***
Maintenance				
Top up Spray (Hylobius)	*£/ha*	£90	£90	
Weeding	£/ha	£285	£260	£310
Cleaning/respacing	£/ha	£70	£35	
General maintenance	£/ha	£220	£200	£220
Forest-scale operations	£/ha	£55	£50	£55
Total maintenance	***£/ha***	***£720***	***£635***	***£585***
Total establishment	***£/ha***	***£2,425***	***£2,100***	***£2,875***
Harvesting				
Thinning	£/m^3 end product	£17	£17	£17
Clearfell	£/m^3 end product	£9	£10	£12
Residue removal	£/m^3 end product	£10	£9	-
Comminution (chipping)	£/m^3 end product	£14	£14	£14

Source: Forest Research

Table A1.6: Range of production costs for coniferous LRF upland

Process Step	Unit	Low	Medium	High	Assumptions
Ground preparation					
Deer Fencing	£/ha			85	20 ha coupes, but only at 10% chance, because large scale deer fencing is non-standard practice at GB level
Draining	£/ha		75	150	Medium 100 m/ha; High 200 m/ha. Current trend is to minimise
Cultivation	£/ha	150	390	460	Lower uses scarifying or shallow ploughing as example, but nil, or a mix of nil and other techniques is possible. Medium uses elements of both excavator mounding and continuous mounding; High is excavator only
Planting					
Plant supply	£/ha	540	600	620	Plant 2,700 stems per hectare SS to achieve 2,500 stems per hectare at year 5. Includes delivery and treatment for RS
Planting, restock	£/ha		200	240	
Planting, new	£/ha	135			
Beat up, labour and plants	£/ha	155	200	350	Lower Y1 10%; Medium Y1 15%; Higher Y1 and Y2 15% and 10%
Maintenance					
Top up spray (Hylobius)	£/ha		90	200	Lower is nil for New Planting, but also sometimes Restock; Medium and Higher is Year 2 and Year 3 spring
Weeding	£/ha	130	260	300	Chemical spot weed. Lower Year 1, Medium and Higher Years 1 and 2
Cleaning/respacing	£/ha		35	70	Medium 5%; Higher 10%. Usually nil but sometimes much more
General maintenance	£/ha	150	200	250	Token allowance for 5 years. Could be nil, or sometimes much more
Forest-scale operations	£/ha	40	50	75	Somewhat token allowance for March fence maintenance, road construction and maintenance and deer assessment and control at large to medium scale forest only, because at smaller scale these costs may fluctuate very widely

Process Step	Unit	Low	Medium	High	Assumptions
Harvesting					
Thinning	£/m³	14	17	22	Thinning costs are weighted toward first thinning, with a proportion of subsequent, owing to prevalence of this in reality for run-of-the-mill upland SS crops
Clearfell	£/m³	7	10	14	Clearfell uses harvester/forwarder working. Extremes of motor-manual felling and skyline extraction on steep or very wet ground and excluded as uncommon legacy requirements, often beyond 'Higher' scale
Residue removal	£/m³	7	9	11	Residue removal is non-standard practice and will usually not apply. Figures relate to recovery of brash mats, excluding potential method improvements. Usually measured in tonnes but approximate conversion used to same unit as used for other harvesting costs (m³) based on solid wood equivalent, albeit this is rough and probably not always so. Cost increased by 10% for Medium and Higher scenarios owing to more frequent of less and more brittle pine brash sites. Lower scenario cost unchanged as best site (SS) is still possible
Comminution (chipping)	£/m³	8	14	22	Note that comminution machine/system outputs vary widely from small scale brash extraction, through whole tree thinning to larger scale roundwood chipping at landing. Any method development figures should be costed with specification parameters for genuine comparison.

Table A1.7: Range of production costs for coniferous LRF lowland

Process Step	Unit	Low	Medium	High	Assumptions
Ground preparation					
Deer Fencing	£/ha		255	570	20 ha coupes, at increased proportion c.f. upland: 33% chance in Medium and 67% in Higher cost scenario, because deer control in upland landscapes may be more difficult
Draining	£/ha		40	75	Reduced c.f. upland. Medium 50 m/ha; High 100 m/ha. Current trend is to minimise
Cultivation	£/ha	150	220	355	Lower uses scarifying or shallow ploughing as example as per upland scenario, although nil, or a mix of nil and other techniques is possible. Medium uses elements of excavator mounding, continuous mounding and scarifying, with Higher is excavator and continuous mounding only
Planting					
Plant supply	£/ha	595	650	680	Costs increased by c. 10% to allow for wider 7 softer species choice incl. SP. Plant 2700 stems per hectare SS to achieve 2500 stems per hectare at year 5. Includes delivery and treatment for RS
Planting, restock	£/ha		200	240	
Planting, new	£/ha	135			
Beat up, labour and plants	£/ha	170	340	430	Increased percentages and labour costs c.f. upland scenario owing to warmer conditions and heavier vegetation. Lower Y1 10%; Medium Y1 15% plus Y2 5%; Higher Y1 and Y2 20% and 10%
Maintenance					
Top up spray (Hylobius)	£/ha		90	200	Lower is nil for new planting, but also sometimes restock; Medium and Higher is Year 2 and Year 3 spring
Weeding	£/ha	145	285	330	Chemical spot weed. Increased cost c.f. upland by 10% owing to weed growth. Lower Year 1, Medium and Higher Years 1,2 and an extra Y3 c.f. upland
Cleaning/respacing	£/ha		70	105	Medium 10%; Higher 15%. Usually nil but sometimes much more

Process Step	Unit	Low	Medium	High	Assumptions
General maintenance	£/ha	160	220	275	Token allowance for 5 years. Could be nil, or sometimes much more. Increase over upland scenario by ~10% owing to vegetation growth, animals and people pressure
Forest-scale operations	£/ha	45	55	80	Somewhat token allowance for March fence maintenance, road construction and maintenance and deer assessment and control at large to medium scale forest only, because at smaller scale these costs may fluctuate very widely. Increased over upland by ~10% owing to fire risk
Harvesting					
Thinning	£/m^3	14	17	22	No change over LRF Conifer, albeit some factors may reduce costs e.g. pine processing, but other increase e.g. less brash, clay soils. Thinning costs are weighted toward first thinning, with a proportion of subsequent.
Clearfell	£/m^3	6	9	14	Clearfell uses harvester/forwarder working. Extremes of motor-manual felling and skyline extraction on steep or very wet ground and excluded as uncommon legacy requirements, often beyond 'Higher' scale. Costs reduced by ~20% in Low and 15% in Medium scenarios owing to greater tree size from greater yield class, firmer/dryer soils and denser roading, but unchanged in Higher scenario for worst sites
Residue removal	£/m^3	7	10	12	Residue removal is non-standard practice and will usually not apply. Figures relate to recovery of brash mats, excluding potential method improvements. Usually measured in tonnes but approximate conversion used to same unit as used for other harvesting costs (m^3) based on solid wood equivalent, albeit this is rough and probably not always so.
Comminution (chipping)	£/m^3	8	14	22	Note that comminution machine/system outputs vary widely from small scale brash extraction, through whole tree thinning to larger scale roundwood chipping at landing. Any method development figures should be costed with specification parameters for genuine comparison.

Table A1.8: Range of production costs for broadleaved LRF

Process Step	Unit	Low	Medium	High	Assumptions
Ground preparation					
Deer Fencing	£/ha	460	710	955	20 ha coupes. Increased provision over coniferous lowland owing to likely higher deer pressure and damage potential. Allowance for rabbit control throughout. Deer exclusion and rabbit key for productive birch.
Draining	£/ha		40	75	Lower than for upland. Current trend is to minimise
Cultivation	£/ha	100	150	245	Mix of nil, scarifying and continuous mounding/ploughing for lower scenario. Mix of nil, mounding and scarifying for medium and high
Planting					
Plant supply	£/ha	575	825	1,075	Bare root only for low but proportions of cell grown for medium and high
Planting, restock	£/ha		220	250	
Planting, new	£/ha	200			
Beat up, labour and plants	£/ha	190	345	425	Labour and plants. Increased allowance for cell plant carry-out
Maintenance					
Top up spray (Hylobius)	£/ha				Nil for Broadleaved
Weeding	£/ha	155	310	360	Chemical spot weed. Added extra for guarded spray. Increased cost c.f. upland owing to weed growth. Applied only in year 1 in lower, medium and higher, applied years 1,2 and an extra Y3 c.f. upland
Cleaning/respacing	£/ha			35	Allowance for 5% in Higher scenario. Usually nil but sometimes much more
General maintenance	£/ha	160	220	275	Token allowance for 5 years. Could be nil, or sometimes much more. Increase over upland scenario by ~10% owing to vegetation growth, animals and people pressure
Forest-scale operations	£/ha	45	55	80	Allowance for March fence maintenance, road construction and maintenance and deer assessment and control at large to medium scale forest only, because at smaller scale these costs may fluctuate very widely. Increased over upland by ~10% owing to fire risk
Harvesting					

Process Step	Unit	Low	Medium	High	Assumptions
Thinning	£/m^3	14	17	22	No change over LRF Conifer, albeit some factors may reduce costs e.g. pine processing, but other increase e.g. less brash, clay soils. Thinning costs are weighted toward first thinning, with a proportion of subsequent.
Clearfell	£/m^3	8	12	16	Costs are tentative, with assumed reduction in outputs of 10% owing to tree form, lower stocking and less brash for trafficking. Harvester/forwarder working.
Comminution (chipping)	£/m^3	8	14	22	Can be very variable as comminution machine/system outputs vary widely from small scale brash extraction, through whole tree thinning to larger scale roundwood chipping at landing.

Table A1.9: Typical costs for SRF establishment and harvesting (£2019)

	Unit	SRF Conifer	SRF Broadleaved
Ground preparation			
Deer fencing	£/ha	£255	£640
Rabbit control	£/ha	-	£70
Draining	£/ha	£40	£40
Cultivation	£/ha	£220	£150
Total ground preparation	***£/ha***	***£515***	***£900***
Planting			
Plant supply	*£/ha*	£650	£825
Planting, restock	£/ha	£200	£220
Beat up, labour and plants	£/ha	£340	£345
Total planting	***£/ha***	***£1,190***	***£1,390***
Maintenance			
Top up Spray (Hylobius)	*£/ha*	£90	
Weeding	£/ha	£285	£310
Cleaning/respacing	£/ha	£70	
General maintenance	£/ha	£220	£220
Forest-scale operations	£/ha	£55	£55
Land rent	£/ha	£131	£131
Total maintenance	***£/ha***	***£851***	***£716***
Total establishment	***£/ha***	***£2,556***	***£3,006***
Harvesting			
Clearfell	£/m^3 end product	£17	£17
Comminution (chipping)	£/m^3 end product	£14	£14
Reversion			
Reversion	£/ha	£1,250	£1,250

Source: Forest Research

Table A1.10: Range of production costs for coniferous SRF

Process Step	Unit	Low	Medium	High	Assumptions
					Ground preparation
Deer Fencing	£/ha		255	570	20 ha coupes. As Coniferous lowland LRF
Rabbit Control	£/ha				Nil expected
Spirals	£/ha				N/a
Draining	£/ha		40	75	As Coniferous lowland LRF
Cultivation	£/ha	150	220	410	As Coniferous lowland LRF, with allowance for greater stocking density in Higher scenario
					Planting
Plant supply	£/ha	595	650	900	As Coniferous lowland LRF, with allowance for greater stocking density in Higher scenario
Planting, restock	£/ha		200	275	
Planting, new	£/ha	135			New planting labour costs of Polar setts is much lower than transplants
Beat up, labour and plants	£/ha	170	340	495	As Coniferous lowland LRF, with allowance for greater stocking density in Higher scenario
					Maintenance
Top up spray (Hylobius)	£/ha		90	230	As Coniferous lowland LRF, with allowance for greater stocking density in Higher scenario, but 'Nil' for Lower scenario is new planting
Weeding	£/ha	145	285	380	As Coniferous lowland LRF, with allowance for greater stocking density in Higher scenario
Cleaning/ respacing	£/ha		70	105	As Coniferous lowland LRF
General maintenance	£/ha	160	220	275	As Coniferous lowland LRF
Forest-scale operations	£/ha	45	55	80	As Coniferous lowland LRF

Process Step	Unit	Low	Medium	High	Assumptions
Land rent	£/ha		131	181	For SRF, 'low' assumes no land rent for low-quality land that has no other agricultural purpose. To adjust, the 'low land rent' figure for SRC is used as the 'medium' cost for SRF, and the 'medium' figure for SRC is the 'higher' figure for SRF. The 'higher' figure for SRC is for high quality agricultural land, which is not expected to be used for SRF.
Harvesting					
Clearfell	£/m^3	12	17	21	Costs are tentative and especially reflect small tree size
Comminution (chipping)	£/m^3	8	14	22	No change over LRF but Caution! Comminution machine/system outputs vary widely from small scale brash extraction, through whole tree thinning to larger scale roundwood chipping at landing. Any method development figures should be costed with specification parameters for genuine comparison.
Reversion	£/ha	1,000	1,250	1,600	Based on mounding and brash mat removal cost assuming 100 t/ha at 5-7 tonnes/hr. Very rough estimate, albeit further refinement possible given time

Table A1.11: Range of production costs for broadleaved SRF

Process Step	Unit	Low	Medium	High	Assumptions
Ground preparation					
Deer Fencing	£/ha		640	850	20 ha coupes. As Broadleaved LRF, except for the Lower scenario 'on farm' where none has been used
Rabbit control	£/ha		70	105	As Broadleaved LRF, except for the Lower scenario 'on farm' where spirals have been used
Spirals	£/ha	625			No canes required for setts
Draining	£/ha		40	75	As Broadleaved LRF
Cultivation	£/ha	45	150	325	As Broadleaved LRF, with an increase for higher stocking density in the Higher cost scenario, and agricultural ploughing and harrowing possible on Lower scenario cost, better farm new planting sites
Planting					
Plant supply	£/ha	950	825	1,335	Lower cost scenario uses Polar setts to minimise total establishment costs on better land, although this is not certain. Higher cost as LRF Broadleaved lowland adjusted for stocking density
Planting, restock	£/ha		220	390	
Planting, new	£/ha	85			New planting labour costs of Polar setts is much lower than transplants
Beat up, labour and plants	£/ha	110	345	675	Medium scenario as Broadleaved LRF, but with greater extremes at Lower and Higher ends
Maintenance					
Top up spray (Hylobius)	£/ha				Nil for Broadleaved
Weeding	£/ha	175	310	445	Added extra for guarded spray. Medium scenario as Broadleaved LRF, but with greater extremes at Lower and Higher ends
Cleaning/ respacing	£/ha			35	As Broadleaved LRF
General maintenance	£/ha	160	220	275	As Broadleaved LRF

Process Step	Unit	Low		Medium		High	Assumptions
Forest-scale operations	£/ha	45		55		80	As Broadleaved LRF
Land rent	£/ha			131		181	As Coniferous SRF
Harvesting							
Clearfell	£/m^3	12		17		21	Costs are tentative and especially reflect small tree size
Comminution (chipping)	£/m^3	8		14		22	No change over LRF but Caution! Comminution machine/system outputs vary widely from small scale brash extraction, through whole tree thinning to larger scale roundwood chipping at landing. Any method development figures should be costed with specification parameters for genuine comparison.
Reversion	£/ha	1,000		1,250		1,600	Based on mounding and brash mat removal cost assuming 100 t/ha at 5-7 tonnes/hr. Very rough estimate, albeit further refinement possible given time

Appendix 2 – Multicriteria Assessment Scores and Ranking of Innovations

Table A2.1 Assessment of innovations against criteria

#	i: Costs	ii: Risk	iii: Wider production impacts	iv: Applicability	v: Timeframe	vi: GHG	vii: Other Env	viii: Uncertainty	a): Duration	b): Size	c): UK capability	d): Supply chain interest
EC1	✓✓✓	✓✓	✓	-	✓✓	✓✓	✓	-	3-5 years	Large	Y	✓✓✓
EC2	✓✓✓	✓✓	✓	-	✓✓✓	✓✓	✓	-	3-5 years	Large	Y	✓✓✓
EC3	✓✓✓	✓✓✓	✓✓	-	✓✓	✓✓	✓✓✓	-	> 5 years	Large	Y	✓✓
EC4	✓✓	-	✓✓✓	-	✓✓✓	✓	-	✓	2-3 years	Large	Y	✓✓✓
EC5	✓✓✓	-	✓✓✓	-	✓✓✓	✓	-	✓	2-3 years	Large	Y	✓✓✓
EC6	✓✓✓	✓✓✓	✓✓	-	✓✓	✓✓	✓	✓	1-2 years	Medium	Y	✓✓✓
EC7	✓✓✓	✓✓	✓✓✓	-	✓	✓	✓	-	2-3 years	Medium	Y	✓✓✓
EC8	✓✓✓	✓	✓✓	-	✓✓✓	✓	-	✓	1-2 years	Large	Y	✓✓✓
EC9	✓✓✓	✓✓	✓✓	-	✓✓✓	✓✓	✓✓	✓	3-5 years	Medium	Y	✓✓✓
EC10	✓✓	-	✓	-	✓✓✓	?	✓✓	✓	1-2 years	Medium	Y	✓
EC11	-	✓✓	✓	x	✓✓✓	-	x	x	<3 years	Small	Y	✓
EC12	✓	✓	✓	x	✓✓	?	?	x	3-5 years	Medium	Y	✓
EC13	✓✓✓	✓✓✓	-	x	✓✓✓	-	-	-	<3 to >5 years depending on exact project	Large	Y	✓✓✓
EC14	✓	✓	-	-	✓	✓✓	✓	x	3-5 years	Small or medium?	Y	✓
EC15	✓✓✓	✓✓	✓	-	✓✓✓	✓✓	✓✓	✓	<=3 years	Medium	Y	✓✓✓
EC16	✓	✓	-	-	✓✓✓	✓✓	✓✓✓	✓	1-2 years	Large	Y	✓✓✓
EC17	✓✓✓	-	✓✓✓	-	✓✓✓	✓	✓	-	2-3 years	Large	Y	✓✓✓
EC18	✓✓✓	✓✓	✓✓	-	✓✓✓	✓	✓✓	-	3-5 years	Medium	Y	✓✓✓
EC19	-	✓✓	✓	-	✓✓	✓✓	✓✓✓	✓	3-5 years	Medium	Y	✓✓
EC20	-	✓✓	✓	-	✓✓	✓✓	✓✓	✓	3-5 years	Large	Y	✓
EC21	✓	✓✓	✓	xxx	✓✓✓	x	x	✓	<=3 years	Medium	v	x
EC22	✓✓✓	✓✓	✓	x	✓✓	x	-	✓	1-2 years	Large	Y	✓✓✓
EC23	✓✓✓	✓✓	✓	-	✓✓✓	✓	✓✓✓	✓	1-2 years	Medium	Y	✓✓✓
EC24	✓✓✓	✓✓	✓✓	x	✓✓✓	✓✓	✓	-	<=3 years	Large	Y	✓✓

#	i: Costs	ii: Risk	iii: Wider production impacts	iv: Applicability	v: Timeframe	vi: GHG	vii: Other Env	viii: Uncertainty	a): Duration	b): Size	c): UK capability	d): Supply chain interest
EC25	✓	✓✓	✓✓	-	✓✓	✓	✓	-	<=3 years	Medium	Y	✓✓
EC26	✓✓✓	✓✓	✓✓	-	✓✓	✓	✓	-	> 5 years	Large	Y	✓✓
F1	✓	✓✓	✓✓	-	✓✓✓	✓✓✓	✓✓	-	3-5 years	Small or medium	Y	✓✓✓
F2	✓✓	✓✓	✓	-	✓✓✓	✓✓✓	✓✓	-	3-5 years	Small or medium	Y	✓✓✓
F3	✓✓✓	✓✓✓	✓✓✓	-	✓✓✓	✓✓✓	✓✓	-	3-5 years	Small or medium	Y	✓✓✓
F4	✓✓	✓✓✓	✓✓	-	✓✓✓	✓✓✓	✓	-	3-5 years	Small or medium	Y	✓✓
F5	✓✓	✓✓	✓✓	-	✓	✓✓	✓	?	<=3 years	Small	Y	✓✓
F6	✓✓	✓✓	✓✓	-	✓	✓✓	✓	✓	<=3 years	Small	Y	✓✓
F7	✓	✓	✓✓✓	-	✓✓	✓✓	✓✓	✓	3-5 years	Small or medium	Y	✓✓✓
F8	✓✓	✓	✓✓✓	-	✓✓✓	✓✓	✓✓	✓	3-5 years	Small or medium	Y	✓✓✓
F9	✓✓	✓✓	-	-	✓	✓	✓✓	?	3-5 years	Medium	Y	✓✓✓
F10	✓✓✓	✓	✓	xx	✓✓✓	✓	✓✓	✓	3-5 years	Small	Y	✓
F11	✓	✓	✓✓✓	x	✓	✓	✓✓	-	<=3 years	Small	Y	✓
F12	✓	✓	✓✓	x	✓✓	?	✓✓	-	<=3 years	Small	Y	✓
F13	✓	-	✓	-	✓	-	-	-	> 5 years	Small	Y	✓
F14	✓✓✓	-	✓✓	x	✓✓	-	-	-	3-5 years	Small	Y	✓
F15	✓	-	✓	x	?	✓	x	-	3-5 years	Small	Y	✓
F16	✓	-	✓	-	?	✓	x	-	3-5 years	Small	Y	✓
F17	-	-	-	-	✓✓✓	✓✓✓	-	?	<=3 years	Small	Y	✓
F18	✓✓	✓✓	✓	-	✓✓	?	✓	✓	3-5 years	Small	Y	✓✓
F19	✓	-	-	-	✓✓✓	-	x	✓	<=3 years	Small	Y	✓
F20	✓	-	✓	x	✓✓✓	✓	?	-	<=3 years	Small or medium	Y	✓✓✓
F21	✓	-	✓	x	✓✓✓	✓	x	x	<=3 years	Small	Y	✓✓
F22	✓	-	✓	x	✓✓✓	xx	xx	-	<=3 years	Small	Y	x

#	i: Costs	ii: Risk	iii: Wider production impacts	iv: Applicability	v: Timeframe	vi: GHG	vii: Other Env	viii: Uncertainty	a): Duration	b): Size	c): UK capability	d): Supply chain interest
F23	✓✓✓	-	✓	-	✓✓✓	✓✓	✓✓✓	✓	3 years	Small or medium	Y	✓✓✓
F24	✓✓✓	✓✓	✓✓✓	-	✓✓✓	✓	✓	✓	<=3 years	Medium	Y	✓✓✓
F25	✓✓	✓	-	x	✓✓	?	✓✓	-	3-5 years	Small	Y	✓✓
F26	?	-	?	xx	✓✓✓	✓	?	x	> 5 years	Small	Y	✓✓
F27	✓	✓✓	✓	xx	✓	✓	✓✓	-	3-5 years	Small	Y	✓
F28	-	?	✓	x	✓	✓	✓	x	<=3 years	Small	Y	✓
F29	?	xx	-	x	✓✓✓	x	?	x	<=3 years	Small	Y	✓✓✓
F30	?	x	-	-	✓✓✓	x	?	x	<=3 years	Small	Y	✓✓✓
F31	✓✓✓	✓✓✓	✓✓✓	-	✓✓✓	✓✓✓	✓✓✓	✓	<=3 years	Small	Y	✓✓✓

Table A2.2 Assessment of potential contribution of innovations to significantly increasing production of energy crops

Theme			Description of innovation
Options assessed as most likely to increase potential production of energy crops significantly			
EC1	M	Increasing yield and resilience in new varieties	Breeding/screening for **rhizome** cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including multi-site trials to test traits of interest
EC2	M	Increasing yield and resilience in new varieties	Breeding/screening for **seed** cultivars with improved traits for: yield, climate, high multiplication potential, potential for growth on marginal/contaminated land, stress resilience (drought, flood, frost, marginal land) or non-invasive hybrids including multi-site trials to test traits of interest
EC5	M	Scaling up production of planting materials	Improved rhizome production, storage and transportation to maintain vigour
EC6	SRC	Scaling up production of planting materials	Production sites for generating planting material need scaling up alongside innovative method development
EC7	M	Planting machinery innovations to increase establishment success and productivity	Machinery, strategies for planting plug-plants to increase establishment success, widen planting window and reduce environmental impact e.g. biodegradable films (not plastic), automated planting systems
EC8	M	Planting machinery innovations to increase establishment success and productivity	Machinery development for automated rhizome planting
EC9	SRC	Planting machinery innovations to increase establishment success and productivity	Planting machinery improvements combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land
EC15	EC	Innovations in harvesting machinery to improve efficiency and access to difficult sites	Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs
EC17	M	Innovations in harvesting machinery to improve efficiency and access to difficult sites	Baling technology: improvement to increase bale density so reducing costs and evaluation of baling chipped material
EC18	EC	Increasing knowledge on optimal harvesting	Research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality
EC23	EC	Improved storage and on-farm pre-processing	Development of optimised storage systems including on-farm storage to maximise feedstock quality and scale-up storage facilities

Theme			Description of innovation
Innovations assessed as likely to increase potential production of energy crops significantly			
EC4	M	Scaling up production of planting materials	Adapted machinery methods for Miscanthus seed production Incorporates investment in sites and machinery.
EC13	EC	Development of new pesticides	Pesticide development and testing combined with new cultivars with pest and disease resistance traits.
EC22	EC	Improved storage and on-farm pre-processing	On-farm pre-processing: needs R&D to design and test strategies and processes e.g. on-farm compaction or washing/leaching to improve feedstock combustion quality.
EC24	EC	Monitoring to improve yield and reduce costs	Development of diagnostic and predictive tools to increase yield e.g. soil mapping to predict yield and remote sensing/drones to monitor in-field crop vigour to inform management and harvesting
EC25	EC	Updated guidance for growers	Decision support and planning tools for use at farm scale level
Innovations assessed as less likely to increase potential production of energy crops significantly			
EC10	EC	Increased establishment success and expansion of planting window	Weed control: herbicide-free agronomy, cover crops, machinery development and testing e.g. mechanical and robotic weeders, cover crops
EC11	M	Increased establishment success and expansion of planting window	Developing strategies to plant at different times of year (non-spring) e.g. autumn planting under plastic to extend the planting window
EC12	M	Increased establishment success and expansion of planting window	Development and testing of soil amendments for marginal or contaminated land
EC14	EC	Updated guidance for growers	Fertiliser information and trials for micro and macro elements
EC16	SRC	Innovations in harvesting machinery to improve efficiency and access to difficult sites	Machinery development for marginal areas (small, wet or sloping sites) and for winter harvesting at wet sites e.g. track-based machinery
EC19	SRC	Improvements in end-of life crop removal	End-of-life crop removal or re-planting strategies have been investigated at small-scale but strategies need developing to minimise impacts on soil carbon and GHGs, including herbicide-free strategies. Successful strategies need demonstrating to growers.
EC20	M	Concerns over difficulties with crop removal	End-of-life crop removal or re-planting strategies have been investigated at small-scale but strategies need developing to minimise impacts on soil carbon and GHGs, including herbicide-free strategies. Successful strategies need demonstrating to growers.
EC21	SRC	Improved storage and on-farm pre-processing	Development of mobile on-farm pelleting

Table A2.3 Assessment of potential contribution of innovations to significantly increasing production of bioenergy from forestry

Theme			Description of innovation
Options identified as most likely to increase potential production of bioenergy from forestry significantly			
F3	SRF - B	Species selection	Selection of species according to characteristics that enhance supply for bioenergy
F4	SRF - C	Species selection	Selection of species according to characteristics that enhance supply for bioenergy
F5	LRF	Provenance choice	Plants from a given original seed source (provenance) are grown in a different location
F6	SRF	Provenance choice	Plants from a given original seed source (provenance) are grown in a different location
F8	SRF	Genetic improvement	Genetic selection uses the selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors
F24	All	Harvesting technology	Design of harvesting machinery and strategies to allow extraction of material from difficult to access sites e.g. sites with steep slopes, reduce impacts from accessing land (e.g. soil compaction), small pockets of woodland. Also includes adaptations for conventional farming machinery to allow extraction from small pockets of woodland, strategies for harvesting currently undermanaged/overstocked mixed species woodland, and for removal of trees felled because of pest or disease.
F31	All	Decision support tools	Decision support tools and platform to provide easy to access information on species, provenance and genetic material, tools to assess land suitability - all with a focus on production for bioenergy as well as conventional timber
Innovations assessed as likely to increase potential production of bioenergy from forestry significantly			
F1	LRF - B	Species selection	Selection of species according to characteristics that enhance supply for bioenergy
F2	LRF - C	Species selection	Selection of species according to characteristics that enhance supply for bioenergy
F7	LRF	Genetic improvement	Genetic selection uses the selection and development of individual trees for specific traits; these may include yield, disease resistance, drought tolerance or other factors.
F9	LRF	Mixed species stand	Biological innovation - choice of species - increased use of mixed species stands when establishing new LRF
F11	LRF	Direct seeding	Process of sowing tree seeds by hand or machine, directly onto a prepared field/forest site; could include the use of for seed encapsulation techniques used for conventional agricultural crops to help improve establishment (inclusion of nutrients, pest deterrents etc).

Theme			Description of innovation
F14	SRF	Changing initial spacing between trees	Closer spacing (up to a point) will result in more biomass per hectare, particularly on shorter rotations which could provide supplies of bioenergy more quickly - improving production.
F18	LRF	Remote sensing for crop monitoring and management	Increasing advances (and cost reduction) in satellite imagery, LiDAR and UAVs (drones), may provide a way of monitoring woodlands.
F23	All	Harvesting technology	Design of a harvesting system that achieves an optimal balance between minimising machine costs and maximising machinery 'output' productivity to achieve a reduction in costs and GHG emissions (i.e. innovations in systems integration).
Innovations assessed as less likely to increase potential production of bioenergy from forestry significantly			
F10	All	Soil preparation by ripping	Mechanical preparation method used for dry soil and for soils that have a deep compacted layer that restricts root growth and plant development.
F12	SRF	Direct seeding	Process of sowing tree seeds by hand or machine, directly onto a prepared field/forest site; could include the use of for seed encapsulation techniques used for conventional agricultural crops to help improve establishment (inclusion of nutrients, pest deterrents etc).
F15	LRF	Fertilising crops using anaerobic digestate or wood ash	Digestate from anaerobic digestion, is a potentially low-cost, nitrogen-rich organic fertiliser resulting from the recycling of food waste, which could be applied to boost biomass production.
F16	SRF	Fertilising crops using anaerobic digestate or wood ash	Digestate from anaerobic digestion, is a potentially low-cost, nitrogen-rich organic fertiliser resulting from the recycling of food waste, which could be applied to boost biomass production.
F17	All	Unconventional soil amendments for carbon removal.	Unconventional soil amendments for carbon removal, biochar, olivine, basaltic minerals, mineral weathering
F19	LRF - C	Manipulating cut-off diameter	Increase or decrease the stem diameter at which the uppermost cut is made separating recovered roundwood produce from tree tops left on site as brash
F20	LRF	Removal of stump to ground level	The lowest cut is made at the point where the stem starts to swell out. The stemwood above this cut is removed from the site but material below this cut (the stump) is usually left on site. Depending on the extent of swelling, the remaining stump can be up to 40 cm high and represents potential additional biomass.

Theme			Description of innovation
F21	LRF - C	Residue removal	Utilise as much of the fine branches and uppermost stem as possible within a silvicultural, harvesting and utilisation system. This is compiled largely from existing technical options which could be combined to minimise operational costs and therefore machinery interventions.
F22	LRF - C	Stump and root removal	To utilise as much of the stump and attached root system as possible within a silvicultural, harvesting and utilisation system.
F25	All	Understorey harvesting	A means of mechanically harvesting coppice species such as hazel, blackthorn, field maple and sweet chestnut when planting in the understorey of another species (e.g. ash) could increase uptake of this approach. For example, techniques which employ cutting rather than smashing or ripping hazel (e.g. Bräcke head) allows for regrowth from the cut stump. Even with such innovation, the approach is likely to require sites larger than 2 hectares to be financially viable.
F27	All	Trees in combination with poultry or grazing animal	Trees have been introduced to open grassland to provide shelter or a more natural environment for free range poultry (layers and broilers hens), sheep and cattle. Trees have also been established to screen intensive poultry units with the added benefit of 'scrubbing' ammonia emissions. This innovation would apply upstream but would require changes to established practices for ground/site preparation stage, planting and establishment and maintenance (mainly protection of the trees).
F28	All	Trees with ground layer biomass crop	To combine a relatively wide-spaced overstorey crop of trees, harvested on an SRF or LFR timescale, with annual biomass production from an inter-row cultivation of a ground layer herbaceous biomass crop, such as a shade tolerant grass.
F29	All	Small scale on-site densification	Small scale on-site densification. For example, torrefaction or pelleting. Would need to develop small scale mobile equipment (sled mounted).
F30	All	Removal of moisture content/drying	Removal of moisture content/drying before transport through forced drying, possible solar options

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