Sustainable Bioenergy Feedstocks Feasibility Study

Task 1 Report

Report for **Department for Business, Energy and Industrial Strategy**
DUNS Number: 218606679

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1 Introduction

1.1 Overview

BEIS' Energy Innovation Portfolio's aim is 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. Bioenergy feedstocks are likely to be an important component of meeting carbon targets and BEIS therefore commissioned this 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 study's specific objectives are:

- To identify innovation opportunities in bioenergy feedstock supply chains and understand their potential for reducing greenhouse gas (GHG) emissions and costs and improving profitability.
- 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.
- To develop high-level, good value-for-money proposals for innovation competitions in bioenergy feedstocks for the Energy Innovation Portfolio.

This report summarises the work carried out in Task 1 of the study which considered four bioenergy supply chains:

- Perennial energy crops: *Miscanthus* and Short Rotation Coppice (SRC)
- Conventional long rotation forestry (LRF)
- Short rotation forestry (SRF)
- Crop residues

For each of these feedstocks, work in the task sought to establish:

- The activities (or process steps) that make up the supply chain from land preparation and preparation of breeding material through to harvested biomass at the farm gate or forest road.
- The costs associated with each activity/process step.
- The greenhouse gas emissions associated with each process step.
- Other environmental impacts and benefits from the supply chain.
- Barriers and challenges faced by landowners in growing the crop.
- Innovations that could address these barriers and challenges.

Information was obtained through a literature review, carried out using the methodology outlined in Section 1.2, which was then supplemented by interviews with a range of key stakeholders, and expert insight from the project team. In addition, insights were gathered through a review of development of SRC in Sweden, which has the largest planted area of SRC in the EU. A list of organisations consulted during the stakeholder analysis is given in Appendix 2.

The focus of this study is the feasibility of a programme for technical and biological innovation, and the literature review was focused on challenges and innovations in these areas. However, in order not to lose valuable insights, particularly from the stakeholder consultation, non-technical barriers and challenges which were identified are also discussed in this report, together with non-technical innovations and policy needs that stakeholders identified. An understanding of these non-technical barriers will be important in the next phase of the study, where as well as assessing the impact that innovations identified could have on costs and GHG emissions, the impact that innovations could have on the attractiveness of bioenergy to landowners will also be explored.

Energy crops are discussed in Section 2, conventional LRF in Section 3 and SRF in Section 4. As many of the innovations identified are applicable to both LRF and SRF, these are considered together in Section 5. Crop residues are considered in Section 6. Section 7 of the report provides a short overview of key points to arise from the analysis.

The methodologies used for the literature review and in the assessment of greenhouse gas (GHG) emissions, which were common across all supply chains are summarised below.

1.2 Literature review methodology

A methodology for the literature review was agreed with BEIS based on a rapid evidence assessment methodology developed previously by Ricardo. This was used by all partners in the project team to ensure consistency across the supply chains. Key steps were:

- Establishing a search strategy and using targeted searches, involving keywords with appropriate search engines.
- Undertaking an initial screening based on initially the title and then the abstract to identify documents that should be included in the literature review.
- Recording all documents identified from the initial screening together with key terms, search engines and criteria.
- Defining inclusion and exclusion criteria for secondary screening.
- Evaluating the evidence using red, amber, green (RAG) ratings for quality, relevance, and significance.

The evidence spreadsheets for each bioenergy supply chain, detailing search terms, inclusion criteria, all evidence identified that was included for review, and RAG ratings, have been supplied to BEIS.

1.3 Assessment of GHG emissions

The study is focussed on identifying innovations which can increase the production of bioenergy feedstocks in a sustainable way. In order to ensure that the innovations identified do not lead to substantive increases, it is first necessary to assess the greenhouse gas (GHG) emissions associated with each process step under current practice. This allows identification of the elements that contribute significantly to the overall GHG emissions up to the farm gate/forest road. In Task 2, the impact of innovations (where their impact on inputs or activities in the production process or on yield can be quantified) on the GHG emissions associated with production will need to be assessed. The methodology used to assess GHG emissions in this Task should also allow this further analysis in Task 2. To facilitate this, it is important that the lifecycle analysis (LCA) GHG data used is sufficiently detailed and transparent regarding input assumptions to allow its manipulation to reflect changes brought about by the innovation. Ideally, in order to ensure consistent treatment of feedstocks, the same data set and calculations, should be used for all feedstocks within the study i.e. energy crops, forestry and crop residues.

Given these considerations, it was decided to use the detailed data set and Excel workbooks developed by North Energy for the project 'Carbon Life Cycle Assessment Evidence Analysis' (North Energy, Forest Research and NNFCC, 2018) carried out for the Energy Technologies Institute (ETI). The project produced estimates of lifecycle emissions associated with energy produced via a variety of conversion technologies from the use of SRC willow and SRC poplar, *Miscanthus*, broadleaf and coniferous LRF and broadleaf and coniferous SRF. Access to the Excel workbooks means that it is possible to extract from these the emissions associated with production up to the farm gate.

2 Perennial energy crops

2.1 Introduction

An energy crop is a plant that is grown for the purpose of producing energy. Energy crops can be processed into solid, liquid or gaseous fuels and used for a variety of end energy uses including for heat and power.

An energy crop needs to be high yielding – it needs to be able to efficiently convert solar radiation and carbon dioxide in the atmosphere into harvestable fuel plus above and below ground carbon; whilst at the same time having:

- minimal agricultural input needs;
- minimal watering needs;
- at harvest,
  - low levels of undesirable components (such as silica and alkali metals),
  - low moisture content, and
  - a consistent composition (within plant, within field and between fields).

The two energy crops that have been most typically grown to date in the UK have been Short Rotation Coppice willow (SRCw) and *Miscanthus*. Other crops which could potentially be grown in the UK include Short Rotation Coppice Poplar (SRCp), Reed Canary grass, and switchgrass. Poplar SRC is becoming a common choice in mainland Europe for dedicated biomass supply options, due largely to the rapid growth and high yields obtainable in a relatively short timeframe, whilst being more frost tolerant than *Miscanthus* and currently more disease resistant than willow SRC varieties (Forest Research/ Uniper, 2016a). However, it has not really taken off in the UK as a dedicated energy crop, having not received initial planting grant support during the previous support rounds of the Energy Crop planting grant scheme (unlike SRCw and *Miscanthus*) (Forest Research/ Uniper, 2016a).

This review has focussed on SRCw and Miscanthus, with some review of Poplar SRC. Reed Canary grass and switchgrass have largely been excluded from the literature review due to limited commercial scale plantings and limited academic research in the UK during the last ten years.

Several varieties of willow have been specifically bred with characteristics well suited for use as energy crops. The willow is planted as cuttings in the spring using specialist equipment at a density of around 10-15,000 cuttings per hectare. After the first year's growth it is cut down to a low stump (or stool) which readily develop multiple shoots, which are left to grow for two to three years before harvesting. A typical plantation will include at least two varieties in field to reduce issues with pests and disease. During the first year the willow can grow up to 4m in height. It is then cut back to ground level in its first winter to encourage it to grow multiple stems (though work in Sweden suggests this does not increase yield with newer lower-stemmed varieties) (Aronsson, 2019); this material is typically discarded because the yield is low and costs for processing would not be recouped. The first crop is harvested in winter, typically two - three years after the cut-back year. The crop is subsequently harvested every three to four years after initial planting, giving a typical total of seven harvests over a 23-year crop life, though some plantations possibly achieving 10 cycles over 30 years. While the equipment needed to harvest willow is not particularly specialist, not many farmers will own their own. Instead, there are contractors who they will typically use.

Miscanthus is a perennial energy crop that can grow to heights of 2.5-3.5 m in one growing year once more than 3 or 4 years old. *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 10,000–15,000 per hectare. After its first full year of growth it can be harvested annually for biomass for 20 years or more. New shoots emerge around March each year, growing rapidly in June to August, producing bamboolike 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. It can be grown successfully on marginal land in all soil types, in both wet and dry conditions, although establishment can be difficult on 'marine clay' type soils. Generally *Miscanthus* produces higher yields when there are higher levels of soil water or rainfall available.

Currently, the area of *Miscanthus and* SRCw grown in the UK for energy is small, at only 9,975 ha in 2018 (Figure 2-1) (DEFRA, 2019). Crops are currently grown across the UK, with localised concentrations in Cumbria, South West, Midlands, South Yorkshire, Norfolk and Lincolnshire. Power production is the predominant end use, with smaller volumes used in boilers to product heat (typically supported under the Renewable Heat Incentive). The yields which are achieved is unknown but based on the lower end of estimated yields (10 odt/ha[1] for miscanthus and 8 odt/ha for SRC) (DEFRA, 2019) these areas could yield just over 94,000 odt of feedstock per year with a primary energy content of 477 GWh. The amount of energy crops grown in the UK has remained relatively static between 2008 and 2018.

In addition to perennial energy crops, annual crops are grown for energy purposes: wheat and sugar beet for the production of bioethanol for use as a transport fuel and maize as a feedstock for anaerobic digestion to produce biogas and biomethane. When these are taken into account, the total area of energy crops in the UK in 2018 was 94,000 ha (DEFRA, 2019). By comparison, in 2018, the UK grew 1.75 million ha of wheat (DEFRA, 2019a).

Figure 2-1: Comparison of land areas used for energy crops with crop-able area and utilised agricultural area

Source: (DEFRA, 2019) (DEFRA, 2019a)

2.2 Production

2.2.1 SRC

The process steps for the cultivation of SRC willow and poplar are similar and are summarised in Table 2-1 with particular aspects discussed in more detail in the following sections. It is important to note that every field can be different, with different challenges and conditions, meaning a blanket style approach in terms of preparation and required steps to achieve a successful plantation is not good practice.

[1] Yields expressed in oven dried tonnes (odt) refer to the mass of biomass if it had a zero moisture content, 1 tonne of material harvested with a 20 % moisture content would be equivalent to 0.8 odt.

Table 2-1: Key process steps in SRC Production

Process steps	Sub-steps	Details
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. Any notable areas following a field assessment should be clearly identified and labelled on a map of the field. Details being recorded should include: the location of foot paths, field boundary, access points to field (can large equipment enter and leave field?), confirmation of the agreed planting area location (if not all of the field is being planted), water courses, any hard outcrops of rock close to or on the surface, any archaeological areas, any service points (water, gas, electricity, telephone), notable areas of weed pressure or problem weed areas in previous crop, any signs of soil compaction or water logging (water reeds), any significant changes in soil type across the area to be planted, any noticeable pest locations (rabbit burrows), any low hanging branches, wires (crops grow to 8m), previous cropping history, drainage channels etc. The extent of preparation steps required will depend on the assessment of the above information.
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	Depending on what is being planted (rods or cuttings), will depend on how deep the cultivator/power-harrow operation is required to be. 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 plant approximately a 20 cm 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.
	Rabbit or deer fencing	Can be required to protect new shoots in year 0 at some sites.

Process steps	Sub-steps	Details
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. AD digestate, dirty water, and sewage sludge are common organic fertilisers applied to SRC after harvesting has occurred. 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 in to 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 which is easily accessible for loading a collection vehicle. If required, drying undercover can be undertaken, either using natural or mechanical ventilation systems.
Reversion	Stump removal/ grinding	SRC plantations are generally viable for 15-25+ years. Once yield or viability of plantation starts to drop, a decision is made to revert the field and start afresh with a new planting, or change the field use. For the reversion of the field to another crop other than SRC, the SRC stumps need to be removed. Typically, coppice stumps are harvested one last time, and the regrowth is sprayed with glyphosate. Stumps are then ground using a powered machine – stump grinder. A break crop may be planted for 1 – 2 years to allow the field to “settle” and for the previous stump and root material to break down before planting. This is not always the case however, and some fields are planted straight back to SRC after some minor steps of reversion have occurred, such as discing to break up the soil.

Source: derived from (Croxton, 2015)

The steps in Table 2-1 represent current practice in the UK, i.e. they can be considered typical for planting carried out now. However, not all steps will be needed for every site, and each step should be reviewed for applicability for each situation and area being planted.

An example lifecycle for SRC crops from pre-establishment to first harvest is given in Figure 2-2. On a 3-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 become less economical to harvest.

Figure 2-2 Growth cycle for Short Rotation Coppice grown on a 3-year cycle

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

2.2.1.1 Initial planning and site preparation

Steps to achieve successful planting need to occur in year -1, which is the summer/autumn before the intended spring planting time. Early ground preparations, including weed control, well in advance, will ensure conditions are optimised before planting. Preparing the ground is site specific and is influenced by the previous land use and vegetation, ecology, soil texture, land drainage characteristics and climatic conditions. Tasks involved include ploughing, sub-soiling if needed and the application of a broad-spectrum herbicide to remove perennial weeds (again if needed). It is essential that the ground is prepared well to minimise future additional costs. The willow cuttings will be planted to a depth of about 15-20 cm, so it is essential to ensure that the soil down to this depth is well structured, consistent and able to retain its moisture (Coppice Resource Ltd, 2006).

Depending on the past use of a field then additional land preparation costs may be added. This is especially the case if it was grassland as leatherjacket control may be needed. This has been one of the biggest causes of plantation failures in the past for both SRC willow and *Miscanthus*.

2.2.1.2 Planting and initial growth

The initial propagation planting material is obtained as either rods (175+ cm) or cuttings (~20cm) from a nursery plantation. Rods are cut down to “cuttings” during the planting operation. More rarely, poles are planted, which are 150-180 cm without any reduction in size during the planting operation; this is a considerably more expensive option, but does achieve maturity quicker, and is usually used for longer term plantings (short rotation forestry rather than coppicing) and are planted at lower densities per hectare.

A vegetable type hand planting machine, “Step” planter, is typically used to plant the willow rods. Operators sit, or stand, on the back of a tractor towed platform feeding the willow rods into a rotating planting mechanism. As the tractor unit moves forward, the planting mechanism rotates, pushing the rods into the ground, leaving about 2 cm of the rod visible above ground. At the same time, the planting machine presses down on the ground around the plant to eliminate air gaps and optimise the surface quality – this pressing also mitigates the risk of slug damage and desiccation of the cutting. A good surface quality will optimise the performance of herbicide post planting (noting that some may choose mechanical weeding instead). If the surface quality is not so good, then additional costs may be incurred as more herbicide applications may be needed.

Cuttings are typically prepared in a factory/production line, where lengths of rod are prepared in a controlled environment and are usually stored in a cool and moist environment. A large percentage of SRCw propagation material is currently imported to the UK each year for planting, and will be produced early in the year, January-March. This process has the benefit of providing a clean, sharp cut and so damage to the planted material is reduced, compared to infield cutting systems if they are poorly maintained.

The main pest after planting can be rabbits and protection against them may be needed for at least two years if numbers are high and grazing is impacting on plant health. Protection is usually by installing rabbit fencing (DEFRA, 2011), which is costly. An application of an insecticide may be needed to control willow beetles if their population reaches critical levels (variety dependent).

One year after planting, the farmer may cutback the crop in late winter/early spring when the shoots are about 4 m tall and about three in number per plant. Cutback involves cutting the growing stems back to around 10 cm tall. This encourages the growth of multiple stems per plant. This cutback is typically needed but not always – high performing fields and different (newer) varieties may not need it.

Fertiliser is usually applied after cutback and then after each harvest (which is when the grower can most easily access the plantation with machinery). Digested or treated sewage sludge is often used. If sewage sludge is not used, then maintenance dressings containing nitrogen, potassium and phosphate will be added. Soil analyses are carried out to check the degree of fertilisation needed.

2.2.1.3 Harvesting and end of life

Following the initial cutback, harvest of the new shoots which grow can take place every 3 – 4 years when they are at about 7-8m in height (Redman, 2018), though some newer, high yielding varieties can now be harvested every two years (Forest Research/ Uniper, 2016a). A willow crop is typically harvested using a modified forage harvester - a heavy duty front end cutting header will have been fitted to a forage harvester used for other crops such as maize. The cut product is usually a 5-20 cm length and is often referred to as a billet at 50-60% moisture content, which is blown out of the harvester into an accompanying tractor/trailer (Schweier & Becker, 2013). Other approaches are available including harvesting as whole stems/rods, where the stems are harvested intact and transported for off-site drying and chipping.

In an evaluation of three different harvest machines, Berhondaray reports that the cut and chip approach is faster and cheaper than whole stem harvesting. Between the two cut and chip machines tested. the self-propelled harvesters was faster than tractor pulled harvesters (Berhongaray, et al., 2013). However, the tractor pulled harvester removed a higher percentage of the available biomass (94.5% against 77.4% for the self-propelled harvester), suggesting scope for optimisation.

The theoretical yield of short rotation coppice is equivalent to 33 oven dried tonnes[2] (odt) per ha per year and this has been achieved in small scale trials in Sweden, although is not often achievable at commercial scale. Yields in practice are variable due to variation in soil and climate. For example, certain soil types such as heavy clay soils, like marine clays can be a limiting factor on yield due to mechanical restrictions, whereas in other soil types, nutrient availability can restrict yield. Annual

[2] An oven dried tonne is a tonne of product that has been completely dried and contains no moisture.

variations in weather patterns can also have an impact, e.g. unseasonal early spring frosts, late spring frosts and long dry spells or drought can all reduce yield.

Short rotation coppice has a productive life of 25 – 30 years and may be harvested 6 – 10 times over that lifetime. Yields may decline over this time, as after a number of harvest cycles, the stump left after harvesting becomes less responsive and loses vigour, producing fewer stems. There seems to be little information available on a UK basis, on the extent of this yield decline, due to most plantations being young.

In UK trials, 17 odt/ha per year have been achieved at the first harvest, with even poorer sites in a national trials network (Forest Research/ Uniper, 2016a) achieving 8 odt/ha per year. Current estimated yields in the UK are in the range of 10 – 12 odt/ha per year on average over the productive life of the plantation (Forest Research/ Uniper, 2016a).

2.2.1.4 Reversion

At the end of a plantation's productive life, it will be removed to make the land available for another crop or be replanted. The plantation life is not set, and it can be shorter or longer depending on the typical harvest interval used and the success of the approach to general plantation management (weed control, pest control etc.) (Forest Research/ Uniper, 2016a). After the final harvest, new shoots are allowed to grow to around 20 cm in height. Glyphosate weed killer is sprayed and the field is either cut with heavy-duty agricultural discs, or the remaining stools can be left to rot down or mulched using a bush hogger/stump grinder depending on how quickly the field needs to be reverted for another crop.

2.2.2 Miscanthus

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. Figure 2-3 shows an example timeline of the *Miscanthus* growth cycle.

Figure 2-3: Timeline of major steps in *Miscanthus* production

<table>
<tr><th></th><th>Year -1</th><th>Year 0</th><th>Year 1</th><th>Year 2</th><th>Year 3+</th></tr>
<tr><td>Jan</td><td rowspan="7">Existing crop</td><td rowspan="3">Site preparation</td><td rowspan="3">Dormancy</td><td rowspan="2">Dormancy</td><td>Dormancy</td></tr>
<tr><td>Feb</td><td rowspan="3">Harvest</td></tr>
<tr><td>Mar</td><td rowspan="2">Harvest</td></tr>
<tr><td>Apr</td><td rowspan="2">Planting</td><td>Topping/Mowing</td></tr>
<tr><td>May</td><td>Gap filling</td><td rowspan="6">Growth</td><td rowspan="6">Growth</td></tr>
<tr><td>Jun</td><td>Gap filling</td><td rowspan="5">Growth</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</td><td rowspan="2">Senescence</td></tr>
<tr><td>Dec</td></tr>
</table>

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

Process step	Sub-steps	Details
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. Any notable areas following a field assessment should be clearly identified and labelled on a map of the field. Details being recorded should include: the location of foot paths, field boundary, access points to field (can large equipment enter and leave field), confirm the agreed planting area location if not all of field being planted, water courses, any hard outcrops of rock close to or on the surface, any archaeological areas, any service points (water, gas, electricity, telephone), notable areas of weed pressure or problem weed areas in previous crop, any signs of soil compaction or water logging (water reeds), any significant changes in soil type across the area to be planted, any noticeable pest locations (rabbit burrows), any low hanging branches, wires (crops grow to 3.5m), previous cropping history, drainage channels. The extent of steps required will depend on the assessment of the above information.
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 more available, with direct seed sowing also being tested, but these come with different agronomic challenges.
	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 chances of soil pests being able to attack the rhizome.
	Herbicide	A pre-emergent herbicide is typically applied to reduce weed competition within 3 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 (year of planting) 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.

Process step	Sub-steps	Details
	Rabbit fencing	Can be required to protect tender new shoots in spring; 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 to manually plant additional material to in fill gaps, after emergence. This process is performed if rhizomes or plantlets have died. This could be due to: pest attack, drought after planting, late spring frost, chemical damage, weed competition (smothering) inadequate planting meaning poor soil covering, or dry soil covering of rhizome leading to desiccation.
	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 weather with warmer temperatures.
	Fertilisation	Nutrient input requirements are generally low, and no fertilisation will be needed on many soils. However if soil analysis indicates that there are very low levels of available nitrogen then a small amount of fertilisation may be needed.
	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)

2.2.2.1 Site preparation

Preparing the ground is site specific and is influenced by the previous land use and vegetation, ecology, soil texture, land drainage characteristics and climatic conditions. These dependencies affect the choices of machinery, the products to be used during land preparation and the time taken. Activities involved include ploughing and the application of a broad-spectrum herbicide to remove perennial weeds. The level and extent of ploughing needed will vary depending on the soil type/quality and past crops. Glyphosate is often used before ploughing to remove previous crops and weeds (Hastings, et al., 2017).

If needed, fencing to prevent rabbits eating the emerging and developing shoots might need to be installed. In terms of pesticides, several diseases can affect *Miscanthus* and require treatment, but this is very rare. Some in the literature report that no pesticides are needed as no serious disease problems have been identified after more than a decade of commercial growing in the UK (McCalmont, et al., 2017).

2.2.2.2 Planting and initial growth

The majority of commercial *Miscanthus* plantations currently use the sterile hybrid *Miscanthus x giganteus*, requiring propagation and planting via a rhizome. Established nursery plantations are harvested using modified potato harvesting equipment and the rhizome collected and separated from soil and then processed at a central factory/processing centre. More than 95% of rhizomes for planting in the UK are produced within the UK. Rhizomes are processed to approximately 50g in weight and can vary in shape and overall size. To achieve good vigour, maintain rhizome moisture, and have sufficient growing points, rhizomes of greater than 30g are usually needed to give good establishment (Atkinson, 2009). Rhizomes can be planted from 10g in the right soil and circumstances, but with higher losses likely, and if maturity wants to be achieved earlier than 3 years after planting, then larger pieces of rhizome can be planted (±150g pieces of rhizome) (Croxton, 2019).

The rhizome is best used harvested fresh and as close to lifting from the ground as possible, to maintain its vigour and rhizome moisture. If a rhizome dries out it will die, and simple effects like a strong wind blowing over rhizomes and exposure to sunlight whilst waiting to be planted on the side of a field can cause rhizome losses or vigour reduction to occur. Rhizomes are similar to a piece of Ginger root in visible appearance and are easily damaged both mechanically and by desiccation. Cold storage after lifting and processing is widely used in rhizome propagation systems, and correct storage humidity is essential to ensure rhizomes don’t dry out in storage. When transporting to fields for planting, depending on distance being transported and weather conditions, rhizomes may require refrigerated transport systems, and as a minimum covered container or curtain sided vehicles will be needed. It should also be noted that when planting 25,000 rhizomes per hectare, at 50g each, this is approximately 1.25 tonnes of planting material per hectare. Therefore, the logistics for lifting, processing, transporting and planting 100,000 ha/y of rhizome requires good planning and investment, with 125,000 tonnes of propagation material needing to be lifted, processed, stored, transported and planted each year. This would require a propagation area in rhizome multiplication of approximately 6,500 ha. While this is a significant tonnage and logistical effort, for context, 6.2m tonnes of potatoes were lifted and transported for use in the UK in 2017 (FAOSTAT, 2019).

Following land preparation, rhizome planting can start. Before planting the rhizomes, the farmer will power-harrow the field to work the soil into a fine, consistent physical quality. Power-harrowing may need to be carried out more than once depending on the quality of the soil and on the opinion of the farmer. Power-harrowing maintains the soil moisture content so that it is at the right level for planting. The rhizomes are typically planted using a manually loaded hand planter. After being planted, the field is rolled to squeeze away air pockets from around the planted rhizomes – this is especially needed in clay type soils, which have a tendency to form air pockets. Air pockets are undesirable as they can lead to rhizome failure, either through drying or rotting. In the literature, costs of rolling are often included within the overall costs of planting; only occasionally is rolling listed as a separately costed activity.

After planting, there may be further application of pesticide and/or fertiliser while the crop matures ready for the production phase. There is variability in the literature concerning fertiliser application rates; inappropriate nitrogen fertiliser use can result in unwanted increases in N_2O emissions (McCalmont, et al., 2017). Nix states that fertiliser and agrochemicals requirements are low (Redman, 2018). Smeets et al. report that there is no consensus on the yield response of *Miscanthus* to nitrogen fertilisation (Smeets, et al., 2009). In the ETI's Refining Estimates of Land for Biomass project (RELB), ADAS presented two *Miscanthus* case studies (Energy Technologies Institute, 2016). Only on one of these two farms is an application of fertiliser shown.

2.2.2.3 Harvesting

Once established, the plantation shifts into the Production phase in year 2. The crop is harvested annually and is expected to reach a maximum height of 3-3.5 metres each year. The consensus view from the literature is that the crop has a useful life of 15-20 years. However, this is not a given and the crop can continue in production beyond 20 years should the farmer desire and if local conditions are suitable (Croxton, 2019).

For years 1-5, there is a yield building phase when yields slowly increase before yields stabilise for the remainder of the plantation life – growing conditions and location will have an influence on the length of this period. Some additional weed control may be needed during the early life of the *Miscanthus* plants; beyond year 1, leaf litter and canopy closure are reported to give effective suppression of most weeds (Croxton, 2014).

The plantation is harvested between February and April each year using a mower conditioner or modified forage harvester[3]. Harvesting equipment is widely available although farmers do not typically own their own, instead hiring in or using contractors.

The *Miscanthus* can be cut and chipped into 1-3 cm lengths by the harvester or left on the floor as longer lengths, ready for a following baler[4]. The baler can bale the cut *Miscanthus* into 500-600kg rectangular Heston bales either immediately after cutting, or more usually the cut *Miscanthus* is left out in swathe on the field for 3-4 weeks to wash (if it rains) and dry (Redman, 2018; Croxton, 2019). Rain washes and leaches the lying crop which can remove undesirable components from the product thereby improving combustion characteristics. Bales have the advantage of a higher bulk density (150-180 kg/m^3) compared to cut chips (90-100 kg/m^3) while chips have the benefit of being cheaper, faster and easier to dry in storage and ready for use in a local only application since their low bulk density can lead to higher than desirable transport costs.

Additional, forced drying may be used either to meet specification or to meet a quality bonus payment (Energy Technologies Institute, 2016).

2.2.2.4 Reversion

Reversion of the land to other uses once the yield has decreased to unprofitable levels requires removal or destruction of the rhizomes. A combination of chemical treatments, where new growth is repeatedly mown and sprayed with glyphosate, and then ploughing followed by rotavating the soil to break up the rhizomes into non-viable fragments was shown to be effective in the EU-funded LogistEC project (LogistEC, 2015).

[3] A forage harvester resembles a large ride on mower which can be used to cut *Miscanthus*. It can chop *Miscanthus* into fine 1-3 cm chips blowing them out the top into a tractor/trailer unit moving alongside or, with the blades removed, crush and compress the *Miscanthus* into 30 cm - 1 m lengths which are left lying on the field floor ready for a separate baling machine to pick up and bale into Heston bales.

[4] Note that the costs shown in this report represent the costs of harvesting for the production of bales

2.3 Costs of production

The two energy crops for which there is enough evidence on costs available to be able to provide baseline production cost data for the UK are willow SRC (SRCw) and *Miscanthus*. This section presents and assesses the costs of production reported in the academic literature, other published literature and from this project's consultation exercise, and then produces a set of representative baseline costs for each process step. These costs are then combined with yield data to produce estimates of the cost per tonne (and GJ) of SRCw and *Miscanthus* at the farm gate. The representative baseline costs are taken from sources where the provenance is known, strong and data is clearly presented in a transparent way. All the data used has been peer reviewed by experts within the Project team. Production costs will inevitably be variable as they are influenced by farming practices and yields. In modelling of costs, different assumptions regarding, for example, agronomic practices will result in different farm-gate production costs. Witzel and Finger found in their review of 51 papers examining the economics of *Miscanthus* cultivation, that key uncertainties are around yields, prices and plantation lifespans (Finger & Witzel, 2016). In order to give some idea of the potential variance in production costs which could be expected, a high and low case has therefore been estimated in addition to the baseline cost. In addition, the impact of land rent on the price of the biomass produced is considered.

2.3.1 SRC

2.3.1.1 Costs in each process step

The costs of production of Short Rotation Coppice (Willow and Poplar) can be broadly split into three phases comprising: establishment; harvest; and finally, reversion. As might be expected, there are variabilities and uncertainties inherent in the costs presented. These may arise because of, for example:

- Differences in soil type and/or condition
- Differences in climate
- Differences in the ways farmers work with their supply companies, which may lead to cost differences
- Differences in plot size.
- Differences in end-product requirements/specifications

Areas of key variability and uncertainty are discussed and quantified at the end of this section.

Establishment is the first lifecycle stage of an SRC crop – it involves preparing the field in readiness for planting, planting the cuttings and caring for the crop until it is ready for its first harvesting cycle. The establishment period for willow is three years (pre-planting, planting, and post-planting). Costs for each of these steps can be highly variable.

For site preparation, costs will vary considerable depending on the site, soil type, drainage and previous use of the field. Heavier or more compacted soils will require additional ploughing and sub-soiling compared to lighter soils, and weathering over-winter may be necessary. Multiple pesticide applications for weeds and insects in addition to mechanical weed control may be needed, particularly when converting from grassland.

Willow rods or cuttings are planted in the spring – various varieties are available, and farmers will usually plant at least two types in a mix in their plantation to mitigate the risk of pests and diseases (Forest Research/ Uniper, 2016a). All willow varieties available are protected by the European Plant Breeders rights so a farmer cannot breed their own stock – hence there is essentially no scope to reduce the costs of the plant material. There are a range of willow SRC suppliers including Coppice Resources Ltd (Coppice Resources Ltd, n.d.), The Poplar Tree Company (Poplar Tree Company, 2012) and Iggesund (Iggesund Holmen Group, n.d.). Usually around 10,000-15,000 willow cuttings/ha are planted in the spring using generally available agricultural machinery that work at a rate of about 1 ha/hour (Forest Research/ Uniper, 2016a) (lower planting densities may be used for longer rotation cycles or site specific factors). (Croxton, 2019).

The use of rods is usually marginally cheaper per planted piece than purchasing prepared 20 cm cuttings but can potentially give higher establishment losses in some cases, requiring gap filling if economically viable. As rods are cut whilst they are being planted, damage can occasionally occur, meaning that disease or drought can set in before growth can occur. Losses are not often significant, but should be considered when making plantation plans, and contingency for additional gap filling may be needed.

Costs associated with the use of pesticides and weed control through the initial growth period will be site dependent, and in many cases reactive according to issues identified during establishment. There is a risk of over spraying by farmers, which will add uncertainty to the baseline costs. Rabbit/deer fencing can be a significant cost in the first year after planting. In most cases, the crop is cut back after the first year of growth to encourage the growth of multiple shoots.

Harvesting and storage costs will be dependent on method and on the yield, as many contributing components are charges as a cost per tonne rather than per hectare.

Typical UK yields are 8-10 odt/ha/year for traditional willow varieties, with newer willow varieties reportedly able to achieve 12-15 odt/ha/year (Forest Research/ Uniper, 2016a). Higher yields of 12-15 odt/ha/year are available from poplar SRC with around 18 odt/ha/year possible from some of the newer poplar varieties seen in Europe (Croxton, 2019).

Achieving higher yields will have a strong impact on the costs of production. Yields of existing plantations could be improved by investing in modern irrigation systems – Schweier reports that many studies show that the plant available water balance is the most important site factor influencing SRC incremental growth rates (Schweier & Becker, 2013). Yields of plantations in planning can be maximised through the choice of variety including choosing poplar instead of willow.

Costs associated with the reversion of the field will depend on the future intended use for the field and how well established the plantation is at the time of wanting to revert the plantation, which will affect how difficult, for example, stump removal is. If the plantation has effectively come to its natural end, 21 – 30 years (7 – 10 harvest cycles), then a number of the stumps are likely to be significant in size, whilst other stumps may already have died or be producing low stem numbers or signs of reduced growth. A total herbicide is applied after final harvest operation and again once new shoots have 10-20 cm of new shoot growth, then mechanical operations are performed to break up the stumps. If planning to plant the field back in to SRC, it is still typical for a field to be planted to another crop for a short time before replanting occurs, but there is often no reason why replanting cannot occur straight away assuming a suitable seedbed for planting can be achieved (Croxton, 2015).

2.3.1.2 Assessment of reported willow SRC production costs

The costs reported from a number of literature sources are shown in Table 2-3. These data have been used along with data obtained during this project's consultation exercise to provide a baseline data set and a production cost per tonne for willow SRC (see Section 2.3.1.3). While the focus was on reviewing recent cost estimates, the lack of data in more recent studies for some steps means that data from a 2001 report was also included in the review (DEFRA, 2001). The data in Table 2-3 suggests that the costs of planting material have dropped since the study in 2001, and this was confirmed in our consultation conversations with experts.

Analysis of these data confirms the finding of El Kasmioui et al. that reliable comparison across studies is challenging because of different assumptions made, different methods used in combination and lack of transparency (El Kasmioui & Ceulemans, 2012). Some data for tasks known to be carried out when growing willow SRC were found to be missing or not representative; gaps were therefore filled using up to date industry data obtained from this project's consultation with key industry experts.

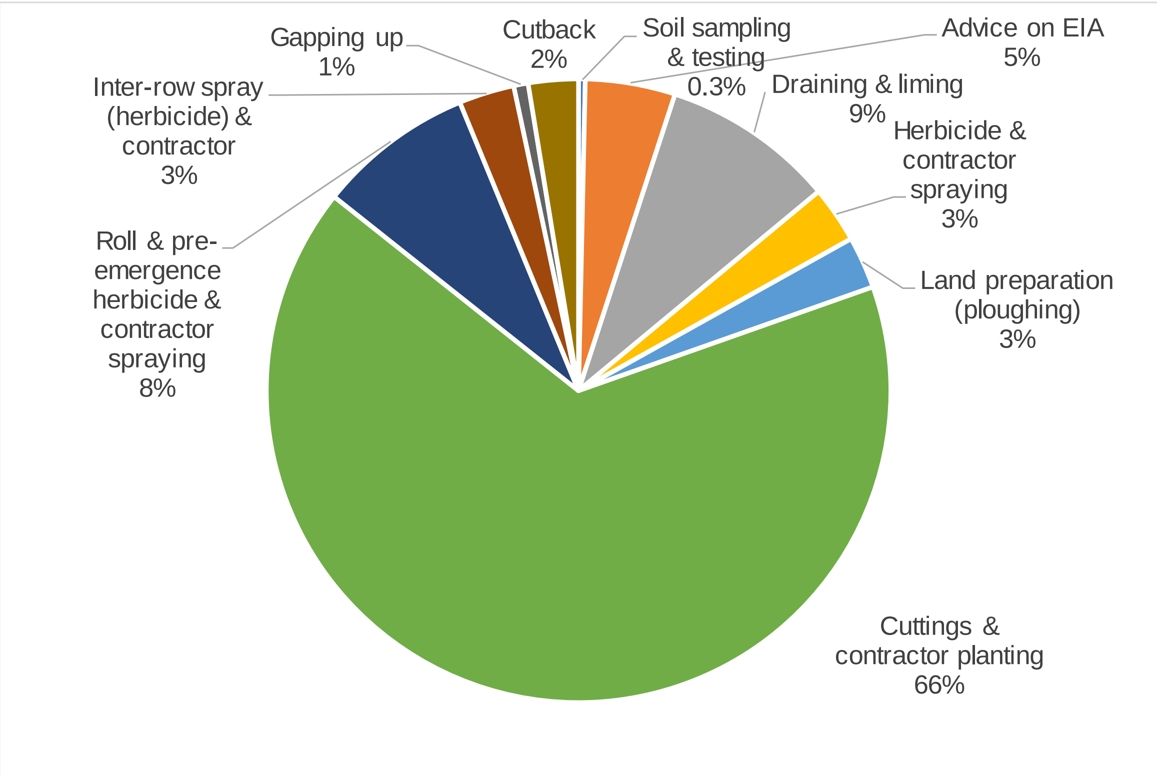
A source with a realistic and detailed breakdown of costs and focussing on a real and more recent case study, is the analysis of Brackenthwaite farm in Cumbria by ADAS for the ETI (Energy Technologies Institute, 2016) (see Box 2.1). The data from this study, combined with data from the separate Characterisation of Feedstocks (CoF) project for the ETI by Forest Research and Uniper (Forest Research/Uniper, 2016b) and other earlier studies were used to prepare a set of typical costs of SRCw production These data were then reviewed with this project's consultees to yield a final data set (Table 2-4) used to calculate the costs of SRCw production (See Section 2.3.1.3).

Box 2.1 SRC production at Brackenthwaite farm

Brackenthwaite farm comprises 323 ha of land used for dairy with a small area used to grow spring barley and triticale for on farm use. The farm previously practiced organic farming but in 2013, due to reductions in the price of organic milk, the farmers chose to move back to non-organic dairying leaving the farm with surplus land. Rather than expand their milk production, which would have required additional investments set against the backdrop of continuing milk price volatility, the farmers decided to grow 29.5 ha of willow SRC for Iggesund Paperboard Mill in Cumbria.

Iggesund and Brackenthwaite farm are working under a 22-year (seven harvest) index linked contract where the farm is responsible for cultivation, fertiliser, weed control, pest control, planting, cutback and final reversion. Iggesund are responsible for harvesting using their own equipment and product haulage to the processing site, with the price paid varying depending on the distance of the grower from the papermill (Redman, 2018).. Iggesund also provide planting advice and access to low price materials (cuttings etc)and ongoing support on crop cultivation. Figure 2-4 gives a breakdown of the cost (£$_{2019}$1,886 per ha) of establishing SRCw at the farm. The costs are based on actual farm data where possible, and estimates from Iggesund for Year 2 cutback and inter-row spraying. The costs of planting, including the cost of the willow SRC cuttings, are the largest cost element (66%) within establishment costs.

Figure 2-4: SRCw establishment costs for Brackenthwaite farm (£$_{2015}$/ha)



Source: Farm data and Iggesund estimate (Energy Technologies Institute, 2016).

Table 2-3: 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] 2010	[3] 2011	[4] 2013	[5] 2015	[6] 2018
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

Activities		Units	Source and year of study (see details below the table)					
			[1] 2001	[2] 2010	[3] 2011	[4] 2013	[5] 2015	[6] 2018
	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	£/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 quoted in the original study using UK GDP deflators[5], and for US costs in [2] using an exchange rate of £1=US$1.6349 in 2003.

[5] 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 2-4: 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
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.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
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 2-3) 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.
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.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
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 2-3).	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 2-3). 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.
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 2-3).	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.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
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 2-3).	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.
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) (2019£ – see Table 2-3).	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 2-3).	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.

Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
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.	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 shows a cost of £16/ha for miscellaneous (2019£ – see Table 2-3).	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.
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 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.	-

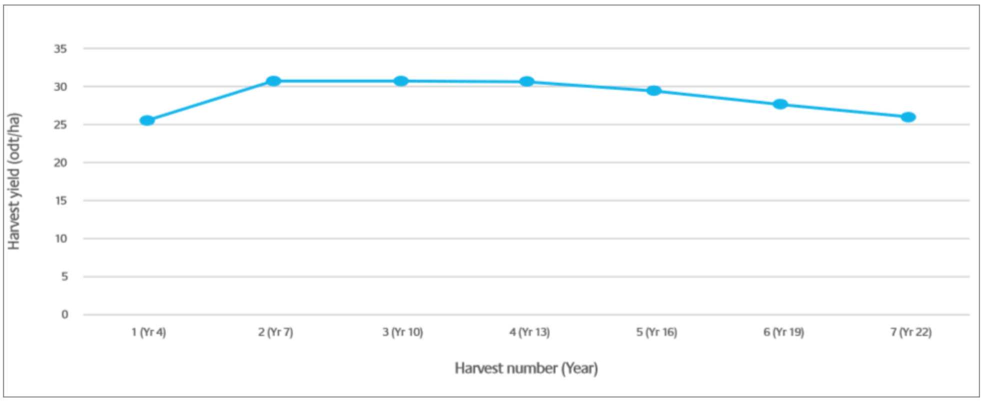
Activity	Requirement	Commentary	Rationale for values used in this study	Impact on final cost
Yield	Yield can be quoted in various ways - oven dried tonnes/ha (odt/ha), fresh tonnes/ha and either per year or on a plantation life average. It is not always clear in the literature which is quoted.	Data from Brackenthwaite farm (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.

2.3.1.3 Estimation of cost of production for SRC

The data in Table 2-3 have been used along with data obtained from this project's consultation exercise to provide a baseline data set for costs for each process step - the assumptions behind each of the data points used is shown in Table 2-4. Note that, for this analysis, land rent, because it varies and because it cannot be improved through technical innovation, is not included in this analysis. Section 2.3.1.4 examines the impact of land rent along with other sensitivities.

The dry matter yield per hectare used to calculate the cost per tonne at the farm gate is taken from the ETI's Characterisation of Feedstocks (CoF) project (Forest Research/ Uniper, 2016a) and RELB project (Figure 2-5) (Energy Technologies Institute, 2016). Yields reported in the literature are variable and the 10 odt/ha used is typical of current varieties grown well.

Figure 2-5: Anticipated yields (per harvest) at Brackenthwaite farm



Source: (Energy Technologies Institute, 2016)

The data in Table 2-3 has been used in a simple cost model to calculate the overall costs of production and these are shown in Table 2-5 for the base case, high case and low case data sets, and as undiscounted and discounted costs (at 5 and 10%). For the discounted values, production has also been discounted so that 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.

Table 2-5: SRC production costs from cost modelling

	Units	Case	Undiscounted figures	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	odt/ha	All cases	205	114	69
Production costs	2019£/odt	Low	35	41	49
		Base	43	50	59
		High	47	56	68
Production costs	2019£/GJ	Low	1.84	2.14	2.57
		Base	2.25	2.61	3.13
		High	2.50	2.95	3.60

The base case (undiscounted) cost of SRCw production (excluding land rent) is estimated to be £43/odt with a high case cost of £47/odt and a low case cost of £35/odt. The discounted (5%) base case cost is £50/odt (with a range for the low and high cases of £41/odt to £56/odt. These values all sit within the range of production costs reported by El Kasmioui et al of between €0.8/GJ and €5/GJ (€2012), equivalent to £0.8-5.26/GJ (2019£) or £16-100/odt (2019£) (El Kasmioui & Ceulemans, 2012). El Kasmioui and this review have both found that a reliable comparison across studies is challenging because of different assumptions made, different methods used in combination and a lack of transparency in many studies. Additionally, the limited roll out of willow SRC limits the amount of data that is available and accessible.

2.3.1.4 Sources of variability and uncertainty in SRC costs

In the analysis above, land rent was not included because it is a variable which would not be affected by technical innovations. However, it is useful to understand the effect land rent 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. This in turn will affect the likely uptake by farmers.

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). For comparison, Wang et al note a typical value of £150/ha/year for land in the UK (Wang, et al., 2012). Defra reports that average rents vary according the type of agreement, tending to be higher for Full Business Tenancy Agreements compared with Full Agricultural Tenancy Agreements with seasonal agreements lower again. Rents are higher in the East of England, East Midlands and West Midlands compared with other regions. There is considerable variation in rents at agreement level. This reflects factors such as the quality of the land and that agreements may be for land only or may also include any combination of dwellings, buildings and other assets.

The impact of having to pay land rent to produce SRC is summarised in Table 2-6, and can be significant. Payment of an average land rent increases costs per tonne of biomass produced by about 45% to £3.8/GJ (for a discount rate of 5%), while at a maximum land rent value, costs are increased by 58%.

Table 2-6: Impact of land rent on base case SRCw production costs (2019£)

Land rent assumption	Rent	Undiscounted costs		5% discount rate	
	£/ha/year	£/odt	£/GJ	£/odt	£/GJ
No land rent	Zero	43	2.3	50	2.6
Low land rent	130	50	2.6	57	3.0
Average land rent	181	63	3.3	72	3.8
Maximum land rent	260	77	4.0	88	4.7

Land rent, which varies according to location, land type and land assets for example, is not the only parameter that can cause a variance in production costs. Other aspects which can lead to variability include:

- Impacts of different climate zones around the UK, incidences of pests and poor weather. Incidents of poor weather for example will have an effect on yield.
- Impact of soil type may increase or reduce costs of soil preparation.
- Impact of past vegetative cover may lead to the need for more or less ploughing and the use of more or less herbicide. Previous use as grassland may lead to the need for additional costs in the form of leatherjacket and wire worm treatment – if available.
- Impact of farming practices which will lead to different approaches depending on the advice received by farmers and their general approach to cultivation.

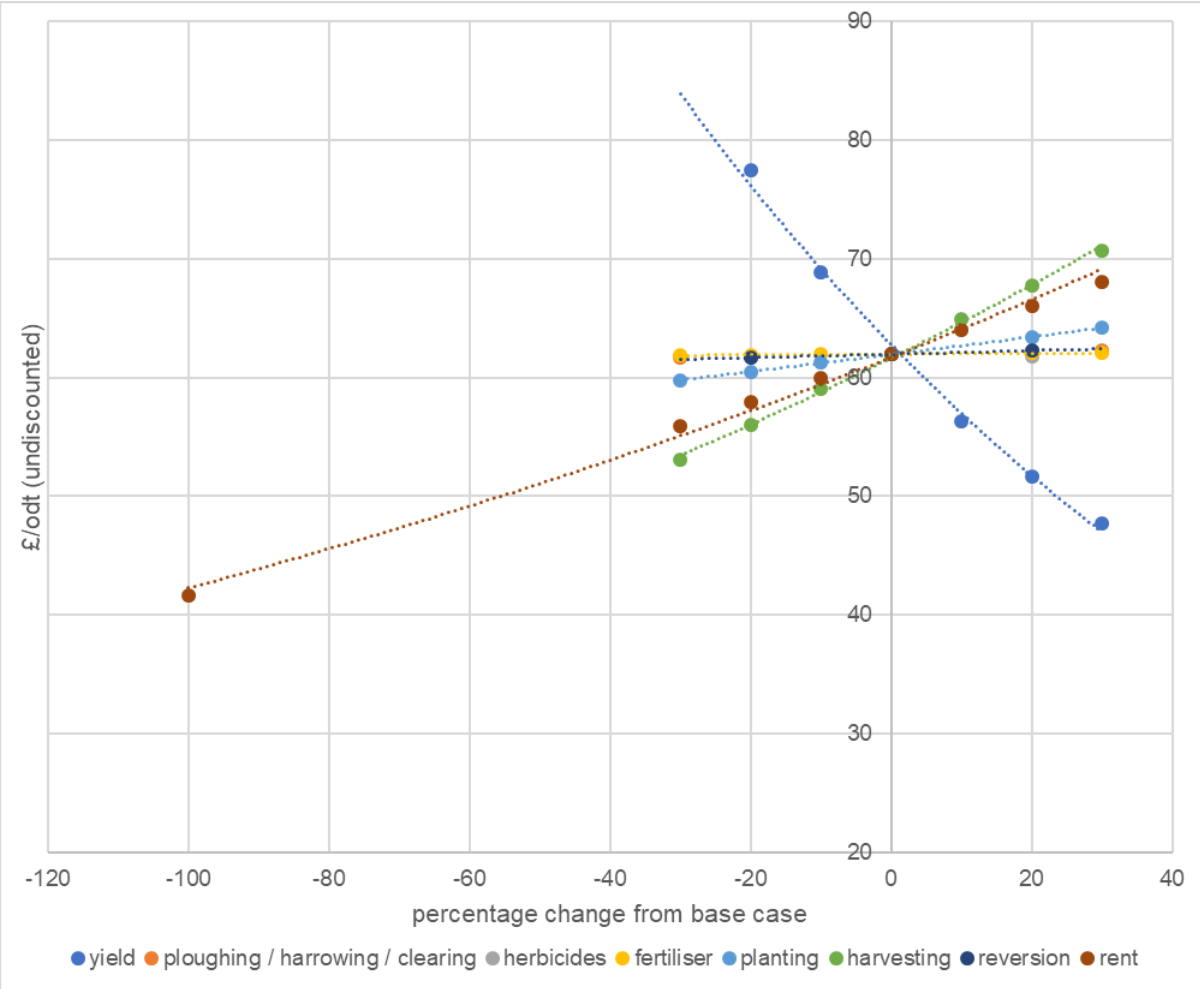
- Impact of quality of land management – poor skills or poor management could for example give rise to the need for more applications of fertiliser and/or weed killers.

Uncertainties which will have an influence on costs of production in the future, and which should be considered include:

- Land rent changes
- Oil price changes
- Uncertainty on rate of change in yield increase with science
- Future yields
- Impacts of changing climate and its effect on yield
- Greater risk of disease and pest damage if the area of energy crop across the UK is increased
- Impacts of new techniques and technologies

Using the data from Table 2-3 with land rent included (base case, undiscounted data), a sensitivity analysis has been calculated to examine the impacts on production cost of: yield, land preparation cost, herbicide cost, pest control cost (rabbit fencing), planting cost, harvesting costs, reversion costs and land rent. The results are shown in Figure 2-6. This demonstrates that the most influential factor is yield with harvesting cost second. This conclusion is supported by others in the literature (Berhongaray, et al., 2013; Buchholz & Volk, 2011; Schweier & Becker, 2013) (El Kasmioui & Ceulemans, 2012).

Figure 2-6: Willow SRC cost of production sensitivity analysis



Innovations to improve yields and reduce harvesting costs may therefore be viewed as having a higher potential cost saving benefit compared to innovation actions elsewhere. Land rent also has a high impact, as also reported by the findings of the Innovation Needs Study for Biomass Heat (Ecofys, E4tech, 2018), but has lower impact than harvest costs. However, where land rent tends to zero, and other cost improvements become incrementally smaller, it will tend to have an increasingly stronger impact. The sensitivity analysis indicates that activities which occur regularly, such as harvesting, have a stronger impact on costs of production than those, which may have high cost, but only occur once.

The importance of yield in determining costs and profitability is also found in the literature. For example, Buchholz used a model to understand the interactions between the different components of the willow production process and how they influence each other. Using his model, he identified those parts of the production process with the greatest potential for providing crop profitability improvements. He concluded that biomass yields have a major impact on the profitability of the crop, finding that increasing yields by 2 odt/ha/year from the base case assumption of 12 odt/ha/year would increase the internal rate of return achieved by the grower by half - from 5.5% in the base case to 8.3%.

Buchholz (Buchholz & Volk, 2011) also observed that:

- Reducing the cost of planting stock and reducing planting density can reduce establishment costs significantly. In comparison, planting speed was observed to have little impact on crop profitability
- Increasing the value of biomass, through for example, developing biorefining has a high impact on crop profitability.
- Providing that biomass densities on field are within a harvester's capability then increasing biomass density within the field is desirable
- Increasing the productive time of the harvester by increasing row lengths and minimising the need to turn increases the overall IRR.
- Bucholz recommended that other factors not analysed during their study which should be considered in future studies including:
    - The impact of loans to finance start-up costs
    - Fiscal policies to support energy crops especially under low yielding conditions
    - The interactions between the different elements of the production system such as trade-offs between site quality and land rent, and between initial field layout and long-term harvesting costs.

To improve yield, Schweier investigated the potential and hence costs of a modern drip irrigation system in Germany. Such a system is reported to cost about €2,000/ha (€2013, equivalent to £2,214 in 2019£) with an annual operating cost of €100/ha/year (€2013, equivalent to £111 in 2019£). As a result of the irrigation, Schweier reported an increased yield from 7.6 to 10 odt/ha/year (Schweier & Becker, 2013). Water deficit is rarely an issue with SRC crops in the UK, so it is unlikely that a drip irrigation system would be cost effective.

2.3.1.5 Summary of costs of producing SRC willow

In this section, the costs of production of Short Rotation Coppice Willow in the literature have been examined. It was found that a reliable comparison across studies is challenging because of different assumptions made, different methods used in combination and a lack of transparency in many studies. Additionally, the limited roll out of willow SRC limits the amount of data that is available and accessible.

To enable a baseline cost of production to be established, a combination of the data from the literature alongside values obtained from this project's consultation exercise was used. The costs of production of SRCw both with and without average land rent are shown in Table 2-7.

Table 2-7: Summary of SRCw production costs (2019£)

	Undiscounted no land rent		Discounted (5%) no land rent		Undiscounted with land rent*		Discounted (5%) with land rent*	
	£/odt	£/GJ	£/odt	£/GJ	£/odt	£/GJ	£/odt	£/GJ
Low case	35.0	1.84	40.7	2.14	49.6	2.61	56.9	2.99
Base case	42.7	2.25	49.7	2.61	63.0	3.32	72.2	3.80
High case	47.8	2.51	56.3	2.97	76.9	4.05	88.8	4.67

* Assuming average land rent

2.3.2 *Miscanthus*

2.3.2.1 *Miscanthus* costs by process step

As with SRC, the cost of production of *Miscanthus* is made up from a number of elements. These can be grouped into three phases of (1) Establishment, which comprises soil preparation, plant material acquisition, weed control and planting; (2) Production which comprises a yield building phase followed by a yield stabilisation phase; and finally (3) Reversion when the plant material is removed and the field made available for a new crop. Costs for each of these are presented and reviewed below.

As might be expected, there are variabilities and uncertainties inherent in the costs presented. These may arise because of, for example:

- Differences in soil type and/or condition
- Differences in climate
- Differences in the ways farmers work with *Miscanthus* companies may lead to cost differences
- Differences in plot size.
- Differences in end-product requirements/specifications

Areas of key variability and uncertainty are discussed and quantified at the end of this section.

Establishment is the first lifecycle stage of a *Miscanthus* crop – it involves preparing the field in readiness for planting the *Miscanthus* rhizomes, planting the rhizomes and caring for the crop until it is ready for its first harvesting cycle. Establishment takes two seasons for the plants to develop ready for production. It is, referred to below as year -1 and year zero. In year -1, the ground is prepared in readiness for planting, which takes place in year zero. As with SRC willow, the extent of soil preparation and so its cost will depend on a number of factors, including the site, soil type, previous use and drainage. The *Miscanthus* rhizomes are planted in the spring at a density of around 25,000 per hectare to achieve a targeted establishment rate of 10,000–15,000 per hectare.

Rhizomes can be purchased from a number of suppliers in the UK including Terravesta[6] and *Miscanthus* Nursery[7]. The costs paid by farmers to these suppliers will be variable depending on a number of factors including volume (related to plantation size), any supplier services and other agreements included in the contract such as an agreement for the supplier to buy the *Miscanthus* product in the future (Energy Technologies Institute, 2016).

The way in which farmers contract with their suppliers has changed in recent years from one of supply and plant to more supply only (Croxton, 2019). This has changed the costs paid by the farmer to the

[6] https://www.terravesta.com/#home,

[7] http://*Miscanthus*nurseryltd.co.uk/

rhizome supplier. In the past, companies such as Bical offered a "one stop" rhizome purchase and plant type contract which relied on a "just in time" type approach whereby the rhizomes arrived at site on the same day as the planter. Weather and other conditions are clearly a risk to this approach and so it is no longer widely used. Instead, farmers will buy the rhizomes only and separately procure the use of a planter so that they can optimally plant their rhizomes at a time to suit the weather, local soil conditions and the farm business.

The cost of buying and planting the rhizomes themselves is the largest cost element of the establishment process (Figure 2-7 in Box 2.2). Costs of rhizome planting ranges from £1,050/ha to £1,825 ha (Forest Research/Uniper, 2016b) (Wang, et al., 2012) (Energy Technologies Institute, 2016). Crops4Energy state that this cost has reduced considerably in recent years and that a total of around £1,500/ha should be assumed (Crops4energy, 2017)[8]. As noted above, this cost of rhizomes can vary according to the agreement made between the supplier and the farmer. As such, only a range of costs can be provided (below) along with the range. For own use, Nix reports that the total establishment cost will be higher, of the order of £3,000/ha including pest control fencing (Redman, 2018).

Unlike SRC, *Miscanthus* is an annual crop, with a limited harvest (in early Spring of Year 2) after the second year of growth (depending on the site) and a full harvest after two years (harvested in Spring of Year 3).

The literature typically reports a 20-year productive life (Energy Technologies Institute, 2016) (Hastings, et al., 2017). After this period, it is suggested that the plantation be removed, in readiness for a new crop – this step is called reversion. Reported reversion costs are estimates only and are of the order of £100/ha (Energy Technologies Institute, 2016), (Wang, et al., 2012). However, as noted above, removal is not entirely necessary, and a farmer could continue production beyond 20 years should he/she wish to and following suitable re-cultivation methods to stimulate new rhizome growth (Croxton, 2019). Field reversion is currently based around the use of a total herbicide (glyphosate) and or grass weed pesticides used in arable crops. However, there is a risk in the future that such pesticide products will not be permitted or approved for use and alternative methods may need to be further developed. *Miscanthus* which has been grown on registered Organic farms has had to be removed previously without the use of pesticides, but there is a degree of uncertainty with this cost.

2.3.2.2 Assessment of reported *Miscanthus* production costs

The costs reported from a number of literature sources are shown in Table 2-8. One of the most complete data sets for the UK comes from an analysis of Abbey and Friars farms by ADAS for the ETI's Refining Estimates of Land for Biomass (RELB) (Energy Technologies Institute, 2016). More details of this are given in Box 2.2. The data from this study, combined with data from the separate Characterisation of Feedstocks (CoF) project for the ETI (Forest Research/Uniper, 2016b) supplemented with data from other studies reported in Table 2.8 were used to prepare an initial consolidated data set on the costs of Miscanthus production. Some data for tasks known to be carried out when growing *Miscanthus* were found to be missing or not representative – gaps were therefore filled using up to date industry data obtained from this project's consultation with key industry experts. The data set was then reviewed with this project's consultees to produce a final data set (set out in Table 2-9). This data was then used to calculate a production cost/tonne for *Miscanthus* which as set out in Section 2.3.2.3.

This analysis of *Miscanthus* costs again confirms the finding of El Kasmioui et al. that reliable comparison across studies is challenging because of different assumptions made, different methods used in combination and lack of transparency (El Kasmioui & Ceulemans, 2012).

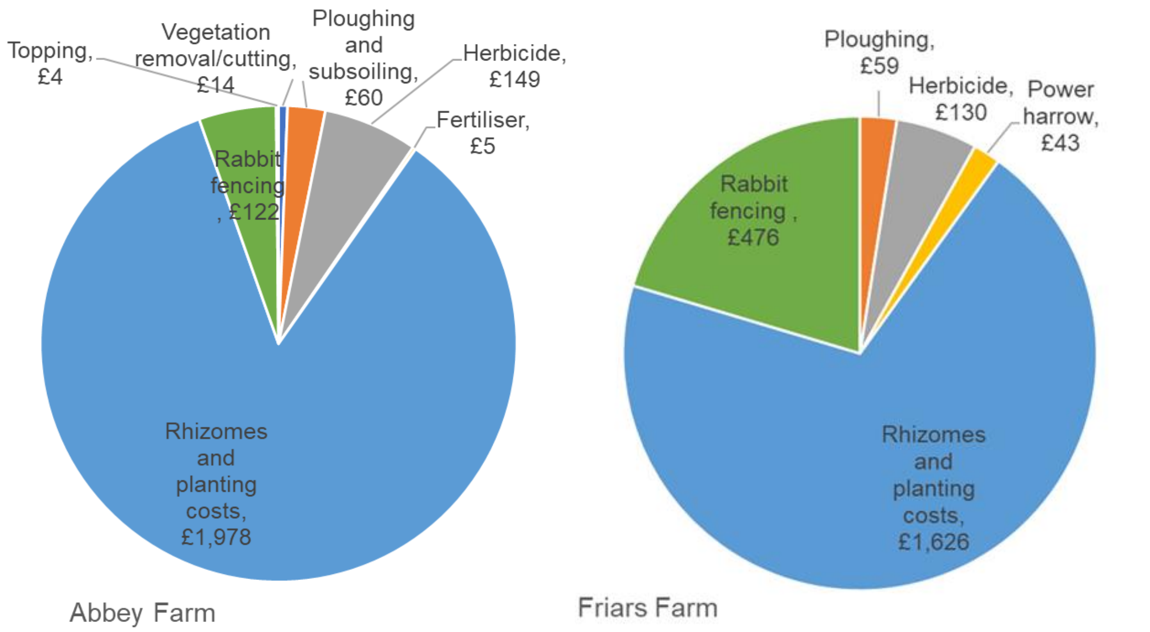
[8] At £1500/ha, we can approximate a cost of between 5 and 10 p/rhizome.

Box 2.1 Miscanthus production at Abbey and Friars **farms**

Abbey and Friars farms are in Norfolk, Friars farm is 734 ha and planted 18.4 ha of in two phases in 2010 and 2011, The 473 ha Abbey farm planted *Miscanthus* in 2013, with an expansion in area in 2015, taking the total area planted to 30 ha. The *Miscanthus* at Friars farm was planted on economically marginal arable land because of difficult soils which yielded less than half the national yield for arable crops. At Abbey farm, land was released from sheep farming; sheep farming production was intensified to minimise the reduction in flock size, and the farm moved from 600 ewes on 90 ha down to 500 ewes on 60 ha. Figure 2-7 shows the costs of establishing SRC at the two farms.

Both farms sell their product (pellets for use in the heat and power sector) to Lincolnshire based Terravesta and both have multi-year index linked contracts with Terravesta for their off-takes. Under their Terravesta contracts, the farmers are responsible for cultivation, harvesting, baling and loading the crop, while Terravesta arrange haulage. The parties have agreed to crop and bale specifications and adjustments to the sale price can be made depending on the product moisture content and contamination levels.

Figure 2-7: Establishment costs at Abbey Farm & Friars Farm (2019 prices, £/ha)



Source: (Energy Technologies Institute, 2016)

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Table 2-8: 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[9], 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

[9] 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 2-9: 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 2-4). 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 found 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 (Table 2-8) (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 (Table 2-8).	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 (Table 2-8).	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 (Table 2-8). 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 (Table 2-8). 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.
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(Table 2-8). 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.

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
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 (Table 2-8).	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 (Table 2-8). 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.
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 (Table 2-8). 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 (Table 2-8). 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.

Item	Requirement	Comment on Lit Review sources	Comment on what was used and why	Impact on cost/odt
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 (Table 2-8).	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 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.
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.	

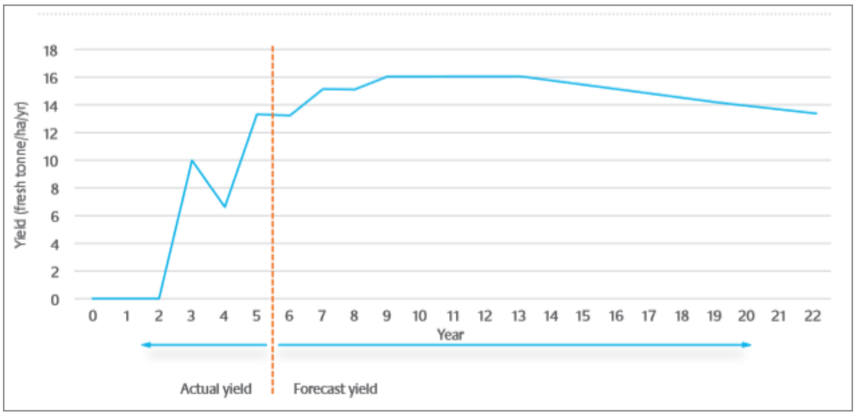
2.3.2.3 Estimation of cost of production for *Miscanthus*

The data in Table 2-8 have been used along with data obtained from this project's consultation exercise to provide a baseline data set for the costs of each step in the *Miscanthus* production process. The assumptions behind the choices made for each data point are shown in Table 2-9. Note that, for this analysis, land rent, because it varies and because it cannot be improved through technical innovation, is not included in this analysis. Section 2.3.2.4 examines the impact of land rent along with other sensitivities.

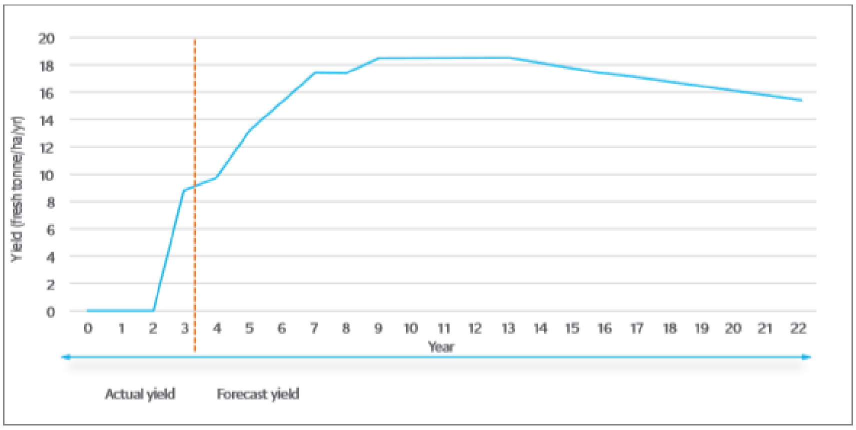
The dry matter yield per hectare used to calculate the cost per tonne at the farm gate represents the anticipated average over 23 years of yields presented by the ETI for Abbey and Friars farms (10.6 oven dry tonnes/ha/year). At Abbey Farm (Energy Technologies Institute, 2016), the first harvest from the 2013 crop yielded 8.82 fresh tonnes per hectare with an estimated future peak yield of around 18 fresh tonnes per hectare. Friars farm reported yields were 10.1 fresh tonnes/ha in 2013 (in year 3 after starting the plantation), 6.7 fresh tonnes/ha in 2014 and 13.4 fresh tonnes/ha in 2015. These historic plus predicted yield profiles, based on previous analysis of *Miscanthus* yield profiles by Terravesta, for Friars farm (A) and Abbey farm (B) are shown in Figure 2-8 (Energy Technologies Institute, 2016).

Figure 2-8: Friars Farm and Abbey Farm actual and forecast *Miscanthus* yields

A: Friars Farm



B: Abbey Farm



The yield figure of 10.6 oven dry tonnes/ha/year is consistent with figures presented by Wang et al. of 10.45 odt/ha/year (Wang, et al., 2012). Other figures in the literature are higher but it is not clear whether these are average yields per 23 years or peak yields.

The data in Table 2-9 have been used in a cost model to calculate the overall costs of production. These costs are shown in Table 2-10 for the base case, high case and low case costs, undiscounted and discounted costs (at 5 and 10%). For the discounted values, biomass production rates have also been discounted so that the cost is a levelised cost of production and represents what the farmer would need to receive to achieve an internal rate of return equal to the discount rate. The costs in Table 2-10 exclude land rent costs.

Table 2-10: *Miscanthus* production costs from cost modelling

	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	28	37	45
		Base	34	46	59
		High	52	70	87
Production costs	2019£/GJ	Low	1.53	2.04	2.52
		Base	1.89	2.58	3.27
		High	2.89	3.88	4.83

Table 2-10 shows a base case undiscounted *Miscanthus* cost of production excluding land rent of £34/odt with a high case cost of £52/odt and a low case cost of £28/odt. The discounted (5%) base case cost is £46/odt (with a range of £37/odt to £70/odt). This compares to production costs reported by El Kasmioui et al of between €0.8/GJ and €5/GJ ($€_{2012}$), equivalent to £0.8-5.3/GJ (2019£) and £16-100/odt (2019£) (El Kasmioui & Ceulemans, 2012). El Kasmioui and this review have both found that a reliable comparison across studies is challenging because of different assumptions made, different methods used in combination and a lack of transparency in many studies. Additionally, the limited roll out of willow SRC limits the amount of data that is available and accessible.

2.3.2.4 Sensitivity analysis for *Miscanthus* costs

In the analysis above, as for SRC, land rent was not included because it is a variable which is not affected by technical innovations. However, it is useful to understand the effect land rent has on the costs of production of Miscanthus. The Defra land rent data used above for SRC (Section 2.3.1.4) has been used in this analysis: £181/ha/year (base case), £260/ha/year (high case) and £130/ha/year (low case). As noted above, there is considerable variation in rents across the country and this must be taken into consideration. The impact of having to pay land rent to produce Miscanthus is summarised in Table 2-11, and can be significant. Payment of an average land rent increases costs per tonne of biomass produced by about 45% to £3.8/GJ (for a discount rate of 5%), while at a maximum land rent value, costs more than doubled (115%).

Table 2-11: Impact of land rent on base case *Miscanthus* production costs

Land rent assumption	Rent	Undiscounted costs		5% discount rate	
	£/ha/year	£/odt	£/GJ	£/odt	£/GJ
No land rent	Zero	34	1.9	46	2.6
Low land rent	130	40	2.2	52	2.9
Average land rent	181	51	2.8	68	3.8
Maximum land rent	260	77	4.3	101	5.6

Land rent, which varies according to location, land type and land assets for example, is not the only parameter that can cause a variance in production costs. Other aspects which can lead to variability include:

- Impacts of different climate zones around the UK, incidences of pests and poor weather (especially frosts) – for example, Zimmerman investigated the incidence of bare patches in *Miscanthus* plantations in Ireland (Zimmermann, et al., 2014)
- Impact of soil type may increase or reduce costs of soil preparation. Heavier more clay like soils may require more attention during ploughing, power-harrowing and rolling.
- Impact of past vegetative cover may lead to the need for more or less ploughing and the use of more or less herbicide
- Impact of farming practices which will lead to different approaches depending on the advice received by farmers and their general approach to cultivation.

Uncertainties which will have an influence on costs of production, and which should be considered include:

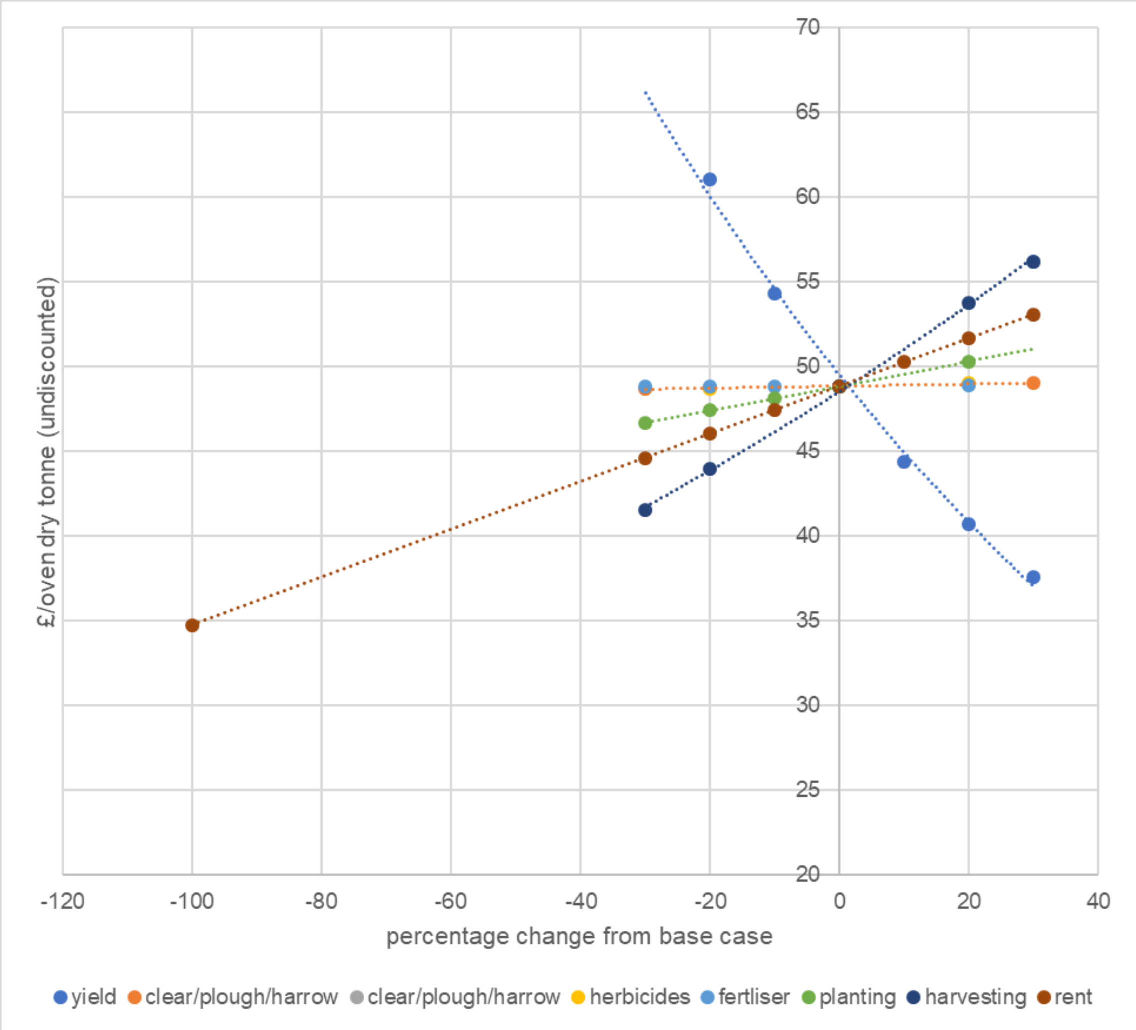
- Oil price changes
- Uncertainty on rate of change in yield increase with science
- Future yields
- The use of fertiliser – as noted above, there is differing evidence available as to the response of *Miscanthus* to nitrogen fertilisers
- Impacts of changing climate and its effect on yield
- Greater risk of disease and pest damage if the area of energy crop across the UK is increased
- Impacts of new techniques and technologies

Using data from Table 2-9 with land rent included (base case, undiscounted data), a sensitivity analysis has been calculated to examine the impacts on *Miscanthus* production cost of: yield, land preparation cost, herbicide cost, pest control cost (rabbit fencing), planting cost (comprising mainly the cost of rhizomes), harvesting costs, reversion costs and land rent.

The results of the sensitivity analysis are shown in Figure 2-9, and the findings are similar to those for SRC. The most influential factor is yield with harvesting cost second, a conclusion that is supported by others in the literature. Wang et al. have reported on the most influential factors on the farm gate production cost of *Miscanthus* (Wang, et al., 2012). They report that yield is the most influential cost factor and that a 50% increase in the yield of *Miscanthus* could reduce the per-unit cost by about 25%. Witzel et al. though report that there are uncertainties in the understanding of *Miscanthus* yields (Witzel & Finger, 2016). Increasing the yield of *Miscanthus* is, therefore, a potentially effective way of reducing *Miscanthus* production cost. Yields will vary according to farm location and growing conditions.

As for SRC, land rent is of secondary importance compared to yield and harvesting costs is. Both the SRC and *Miscanthus* sensitivity analyses indicate that activities which occur regularly, such as harvesting, have a stronger impact on costs of production than those, which may have high cost, but only occur once.

Figure 2-9: *Miscanthus* cost of production sensitivity analysis



Note: Base case data taken from Table 2-9 (average data)

2.3.2.5 Summary of cost of Miscanthus production

In this section, the costs of production of *Miscanthus* in the literature have been examined. As for SRC, and as also reported in the literature, it was found that a reliable comparison across studies is challenging because of different assumptions made, different methods used in combination and a lack of transparency in many studies.

To enable a baseline cost of production to be established, a combination of the data from the literature alongside values obtained from this project's consultation exercise were used. This has resulted in the estimated *Miscanthus* costs of production, both with and without average land rent, shown in Table 2-12.

Table 2-12: Summary of *Miscanthus* production costs (2019£)

	Undiscounted no land rent		Discounted (5%) no land rent		Undiscounted with land rent*		Discounted (5%) with land rent*	
	£/odt	£/GJ	£/odt	£/GJ	£/odt	£/GJ	£/odt	£/GJ
Low case	28	1.53	37	2.04	40	2.21	52	2.90
Base case	34	1.94	46	2.63	51	2.89	68	3.83
High case	52	2.89	70	3.88	77	4.25	101	5.60

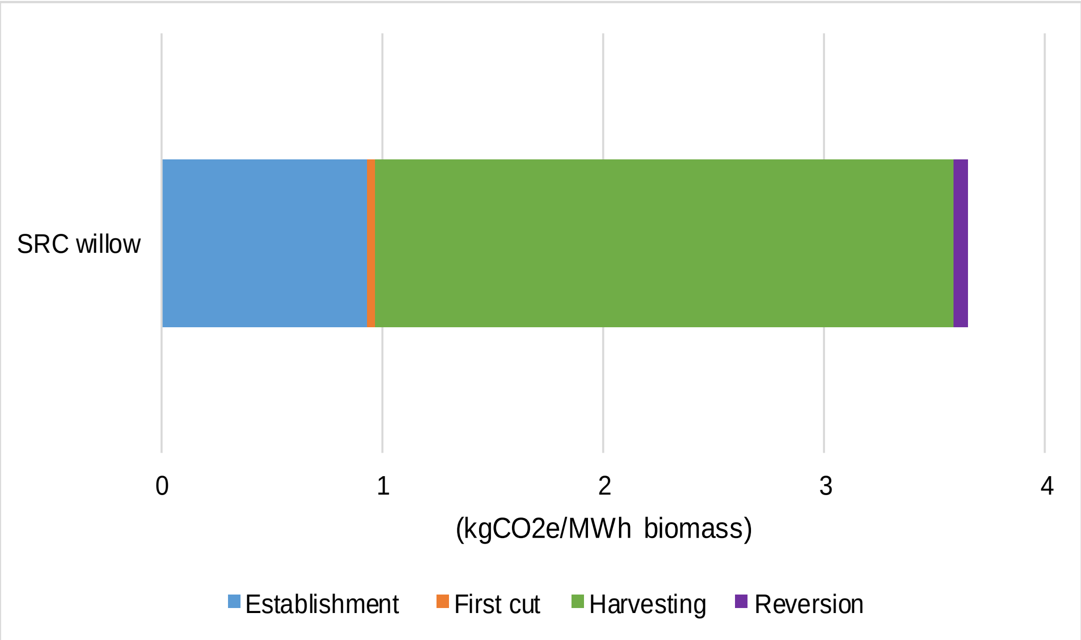
* Assuming average land rent

2.4 GHG emissions from production

2.4.1 SRC

GHG emissions from 'typical' production of SRC willow from planting through to harvest and including emissions from grubbing up the plantation at the end of its life, are shown in Figure 2-10. 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 are estimated to be 3.6 kg CO_2/MWh of biomass feedstock for SRC willow. A further breakdown of emissions by source is shown in Figure 2-11 and key assumptions in the estimation of emissions in Table 2-13.

Figure 2-10: GHG emissions from production of SRC by process step

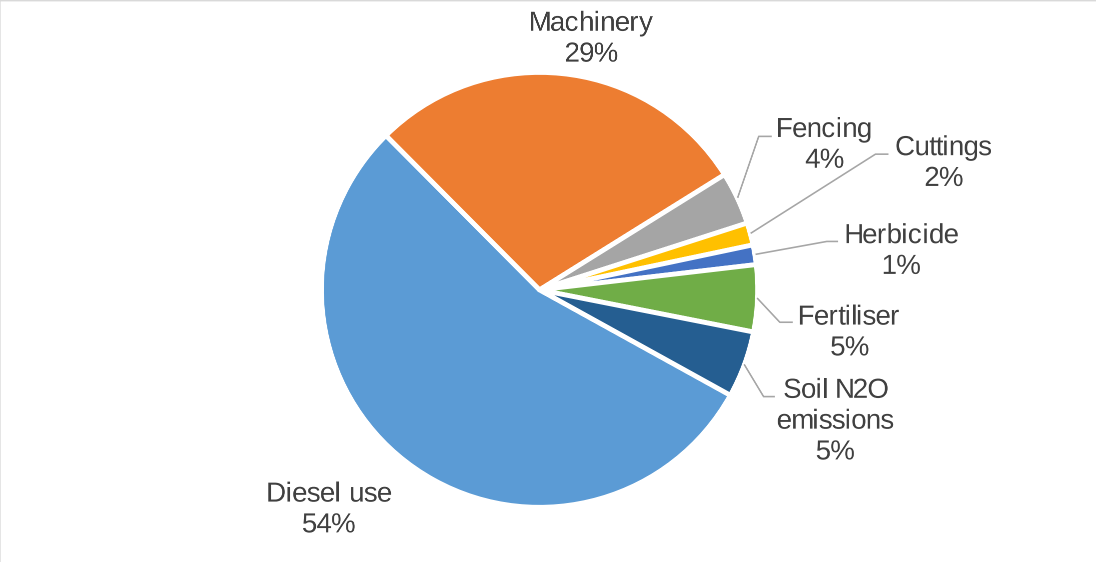


Source: derived from (North Energy, Forest Research and NNFCC, 2018)

Emissions arise principally in the harvesting step, and within that mainly from diesel use, although the 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 e.g. transport vehicles. These emissions also become more significant in the overall emissions, as emissions from other sources are relatively low. Diesel use contributes the highest share to overall emissions in the establishment phase (35%), but production of nitrogenous fertiliser and the soil N_2O emissions arising from its application also contribute significantly (19% each).

The sensitivity of GHG emissions to assumptions about yield and other production parameters are shown in Figure 2-12, with the variation in key parameters detailed in Table 2-13. As for cost, and as would be expected, yield has a significant impact on emissions per MWh of biomass produced. The amount of N fertilisation which is required also has a significant impact, and the rate of soil N_2O emissions will also have some impact. The impact of assumptions about the carbon footprint of agricultural machinery, and fertiliser production is insignificant.

Figure 2-11: Sources of GHG emissions in production of SRC willow



Source: derived from (North Energy, Forest Research and NNFCC, 2018)

Figure 2-12: Sensitivity of GHG emissions in production of SRC willow

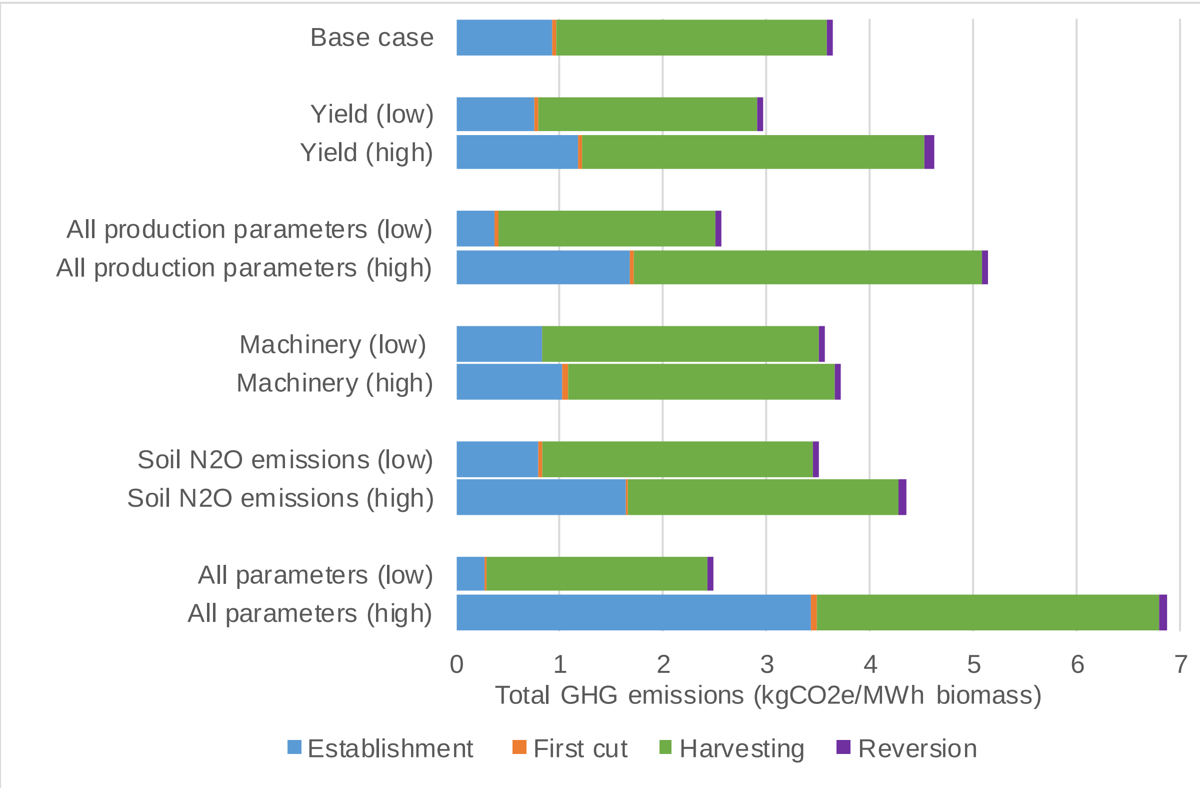


Table 2-13: Key assumptions about SRC production for estimation of GHG emissions

Parameter	unit	Low	Average	High
Cuttings	number/ha	15,000	17,500	20,000
Annualised yield	green t/ha per year	28	24	20
Annualised yield	odt/ha per year	14.0	11.4	9.0
Plantation lifetime	years	25	27.5	30
Fertiliser (at establishment)	kg N/ha	0	45	90
Herbicide (at rotation)	kg a.i./ha*	0	0.45	0.9
Herbicide for grubbing up		1.8	1.8	1.8
Fencing for pest control		not required	Electric fence (some of area)	Electric fence (all of area)

*a.i. = active ingredient

2.4.2 *Miscanthus*

GHG emissions from 'typical' production of *Miscanthus* from planting through to harvest and including emissions from grubbing up the plantation at the end of its life, are shown in Figure 2-13. As for SRC, they exclude changes in emissions from soil carbon 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 are estimated to be kg CO_2/MWh of biomass feedstock. A further breakdown of emissions by source is Figure 2-14 and key assumptions in the estimation of emissions in Table 2-14. Note that applications of fertiliser 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. A value of zero is therefore taken for both the low and average case. The value for the high case is retained from the original data set but represents an extreme value.

Emissions arise principally in the harvesting step from diesel used in harvesting machinery.; emissions from other stages are low, particularly as little or no maintenance of the crop is required. Emissions from machinery are not as significant as with SRC, reflecting higher utilisation factors for the machinery.

Table 2-14: Key assumptions about *Miscanthus* production for estimation of GHG emissions

Parameter	unit	Low	Average	High
Rhizome Planting Rate	number/ha	15,000	17,500	20,000
Life of plantation	Years	20	17.5	15
Annualised yield	green t/ha.a	14.7	13.3	11.9
Annualised yield	odt/ha.a	12.5	10.7	8.9
Herbicide for establishment	kg a.i./ha	1.4	2.5	3.6
Fertiliser for maintenance	kg N/ha.a	0	0	50
	kg P_2O_5/ha.a	0	0	10.3
	kg K_2O/ha.a	0	0	84.4
Herbicide (for grubbing-out)	kg a.i./ha	1.4	2.5	3.6

a.i. = active ingredient

Figure 2-13: GHG emissions from production of *Miscanthus* by process step

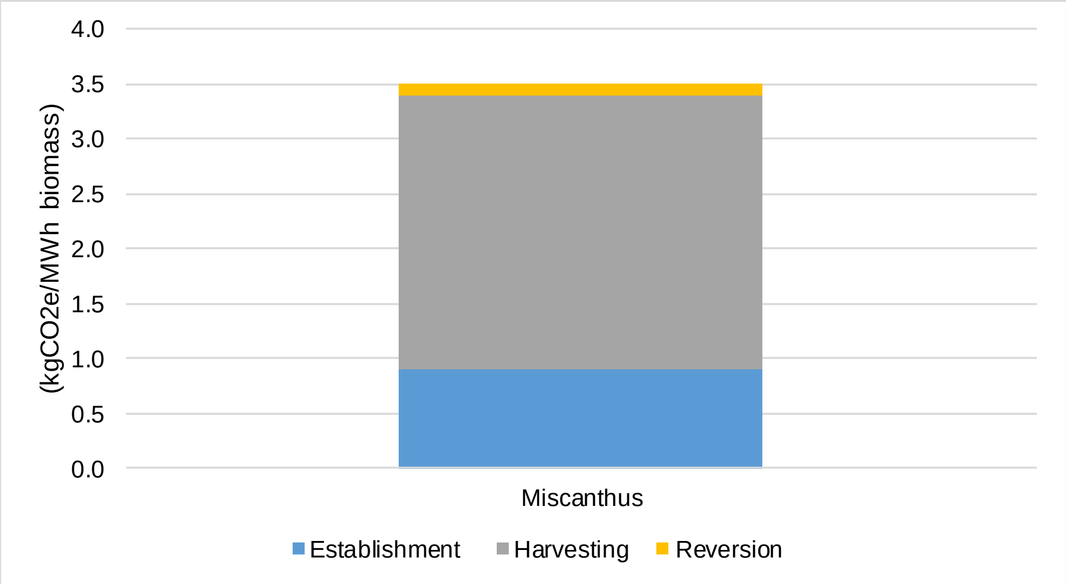


Figure 2-14: Sources of GHG emissions in production of *Miscanthus*

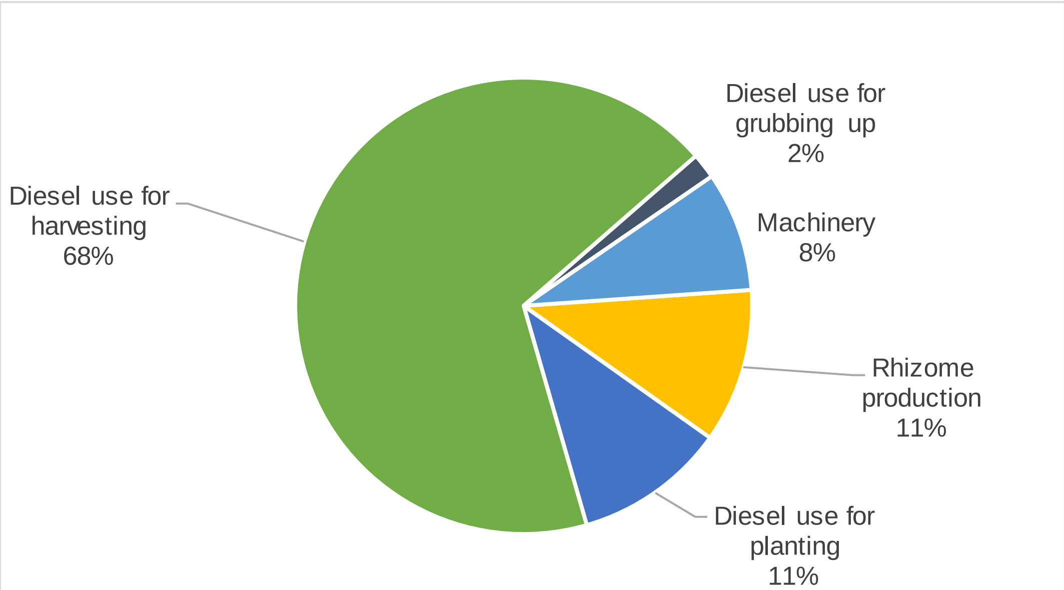
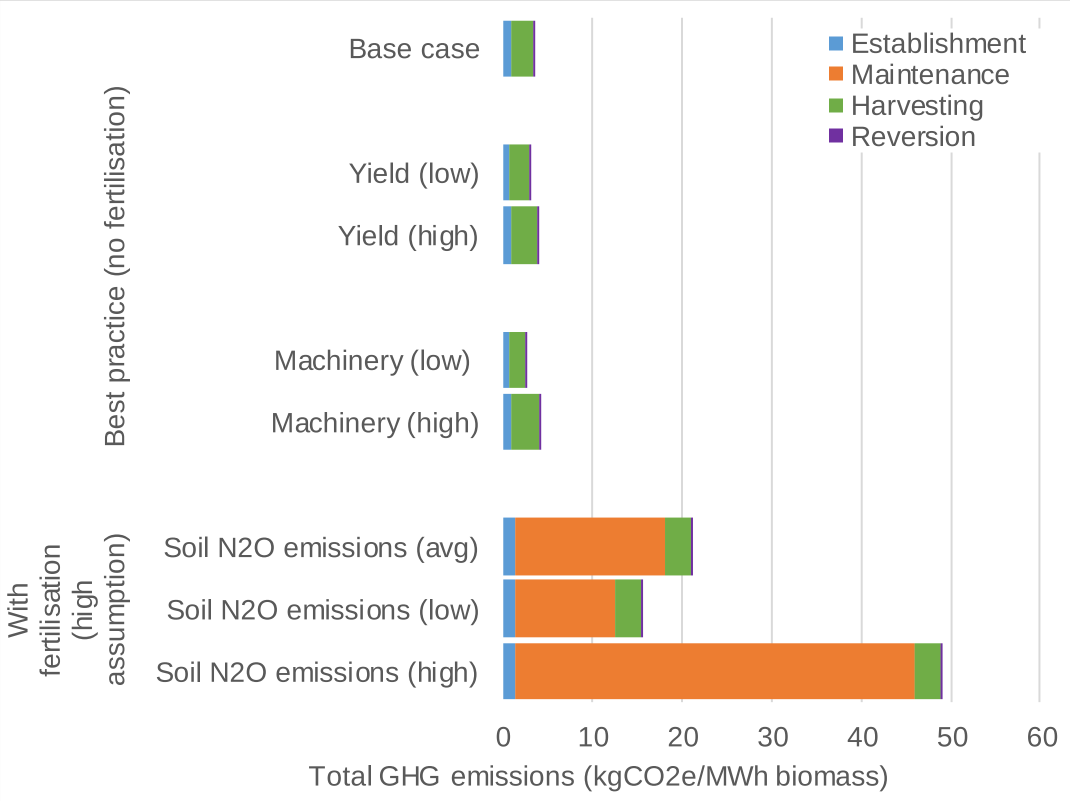


Figure 2-15 shows that as with SRC, yield has an impact on emissions per MWh. In cases where fertilisation is assumed (the 'high' case), the sensitivity to assumptions about the rate of soil N_2O emissions is higher than for SRC due to the assumption about regular application of nitrogenous fertiliser.

Figure 2-15: Sensitivity of GHG emissions in production of *Miscanthus* to key parameters.



2.4.3 GHG fluxes associated with soil carbon changes

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 2-15. 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 2-15 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 2-10 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.

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 2-15 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 2-15: 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)

2.5 Other environmental impacts and benefits

2.5.1 Introduction

A comprehensive literature review on the potential environmental impacts of bioenergy crop deployment was produced in 2009 (Rowe, et al., 2009). In this section this highly cited review is updated with a review of literature published since 2009 focused on the UK, drawing on literature from northern Europe where information from the UK was limited. To reflect developments in the field of environmental assessment since 2009, environmental impact categories included in this section are based on the Natural Capital (NC) approach used in the UK government "25 Year Environment Plan" and Defra's "The Future Farming and Environment Evidence Compendium". This work therefore considers the evidence for the environmental benefits and costs of bioenergy crop production (to farm-gate) on the following NC based categories, quantifying the scale of these where possible and identifying gaps in the evidence.

- **Clean and plentiful water**
  Implications for water quality and water availability, taking into account changes in water use by different crops or management practices.

- **Healthy soils**
  Impacts on soil health such as changes in erodibility, compaction, water holding capacity and fertility and also the remediation of contaminated or degraded soils.

- **Flood risk**
  Impacts linked to healthy soil and clean water via changes in water infiltration rates and impacts on over-land water flow during extreme flooding events.

- **Clean air**
  Impacts on air quality of different crop types accounting for both air filtration services but also release of contaminants such as pollen or ammonia.

- **Wildlife habitats**
  Impacts on biodiversity including both species diversity and abundance resulting from impacts on food resources and shelter due to changes in crop types.

- **Landscape, tourism and rural Heritage**
  Societal impacts including potential physical impacts on archaeological features, the use of the land for outdoor exercise and activity, and the role of the visual landscape in peoples' sense of place and wellbeing. The value is related to avoided health care costs.

There is limited empirical evidence on the environmental impacts of non-food bioenergy crops other than willow SRC and *Miscanthus*, due to the limited scale of bioenergy crop planting. This assessment is therefore focused on these two species. Parallels however can be drawn between willow SRC and other SRC species such as poplar and between *Miscanthus* and other energy grasses.

Environmental impacts are presented as a comparison to a counterfactual. The counterfactual used in the presented research is predominantly agricultural grasslands and croplands, reflecting the restriction placed on planting of any crop, including energy crops, on areas of high conservation values (ancient woodland, peat bogs etc.). Whilst agricultural grasslands and croplands are the most likely location for any future expansion of bioenergy cropping it must be noted that planting outside of these areas may have significantly different environmental impacts than those suggested here.

2.5.2 Clean and plentiful water

Evidence indicates that willow SRC and *Miscanthus* cultivated in agricultural landscapes improve water quality but can reduce water availability in drier sensitive areas – although impacts will depend on the scale of planting. The impacts on water availability are likely to be a concern under future climate change projections in some areas of the UK. (Dimitriou, et al., 2012; Langeveld, et al., 2012; Christen & Dalgaard, 2013; Ferchaud & Mary, 2016; Whitaker, et al., 2018; Holder, et al., 2018).

Improvements in water quality are in large part related to the decreased use of herbicides, pesticides and fertilisers in comparison to conventional crops and grassland. However both crops, but especially willow SRC, are noted for their ability to remove excess nitrogen from soils (Langeveld, et al., 2012; Ferchaud & Mary, 2016; Skenhall, et al., 2013; Dimitriou, et al., 2012). Willow SRC has been shown to be an economic method for the treatment of waste water and sewage sludge (Dimitriou & Rosenqvist, 2011). Using SRC as part of buffer strips along rivers has for example been predicted to result in the retention of 30-99% of nitrate and 20-100% of phosphate run off as well as removing pesticide contamination (Christen & Dalgaard, 2013).

Reductions in water availability are caused by the higher water demand of these crops compared with grassland or cropland. High resolution hydrological modelling for west Wales showed that planting at an ambitious level of 50% of the existing improved pasture with either crop resulted in limited impacts on water yield and stream flow (+/- 5%) in the majority of catchments (Holder, et al., 2018). However, up to a 50% reduction in flow was apparent in a few streams, highlighting levels of spatial variation.

2.5.3 Flood Risk

SRCw and *Miscanthus* crops have several properties that could help mitigate flood risk in agricultural landscapes: they reduce surface run-off and increase base flow, decreasing soil drying and increasing evapotranspiration which increases the potential to absorb flood waters (Christen & Dalgaard, 2013; Holder, et al., 2018). These changes reduce soil erosion and thus the risk of silting in rivers and streams (see soil health) and increase hydrological roughness, especially in winter, potentially slowing flood water movement and trapping debris (Environment Agency, 2015).

Directly assigning quantifiable flood mitigation potential requires detailed site-level hydrological modelling. In contrast, the current scientific literature has focused on exploring characteristics known to be potentially beneficial to flood mitigation rather than location specific case studies (see references above). A study from the USA used the "Soil and water assessment tool (SWAT)" model to explore the flood regulation potential of *Miscanthus* in two watersheds in the USA but whilst they did find a reduction of 12% in erosion risk they found no significant effects on flood regulation across a range of scenarios with planting rates between 4 -71 % of the land area (Cibin, et al., 2017).

There is information from industry on this topic, for example Iggesund and local land owners' experience during severe flooding in Cumbria reported benefits of SRCw including the prevention of soil erosion and trapping debris during flooding, with the Cumbria Rivers Trust expressing interest in the potential of the crop to slow flood water by increasing hydrological roughness[10].

2.5.4 Healthy soil

In comparison to agricultural soil under conventional management, there is consensus in the literature that SRCw and *Miscanthus* improve soil health. Improvements include: reducing soil erosion and increasing soil (aggregate) stability; improving water infiltration and being broadly beneficial for soil fauna (Bourgeois, et al., 2015; Holder, et al., 2018; Rowe, et al., 2009). These benefits are a result of the reduced tillage, inputs and machinery usage on the land required for perennial energy crop cultivation.

Energy crops (SRCw, *Miscanthus* and Reed Canary Grass) have potential to be cultivated on contaminated or degraded land and used for phytoextraction, phytodegradation or phytostabilization (Nurzhanova, et al., 2019; Ruttens, et al., 2011). Phytostabilization uses plant varieties that restrict contaminants in the root system, therefore reducing erosion and off-site losses and minimising uptake into the above-ground biomass, so minimizing food-chain transfer, risks to wildlife and risk of contaminant dispersal when the biomass is used for energy. In addition, growing perennial energy crops on contaminated/degraded soils can restore soil health (Bourgeois, et al., 2015). *Miscanthus* and Reed canary grass have been reported to have potential for phytostabilization of heavy metals and metalloids, as contaminants tend to remain in the roots (Nsanganwimana, et al., 2014). SRCw can accumulate and tolerate heavy metals, especially cadmium, which is present in sewage sludge applied to agricultural land and in many contaminated soils. The levels of phytoextraction do not appear sufficient for element recovery and the scale of soil remediation which can be achieved is unproven. Specific SRCw clones (*Salix Klara* and *Salix Inger*) grown in Sweden have demonstrated potential for phytostabilization of a range of heavy metals and metalloids on contaminated land (Enell, et al., 2016).

In the UK, Seven Trent Water and Cory Environmental performed a range of trials evaluating SRCw and *Miscanthus* on contaminated land sites, and landfill sites, and reported that establishment was often very challenging due to the nature of the soil. This is an area that requires further ongoing research and quantification of the potential biomass resource which could be delivered.

[10] (http://biofuel.iggesund.co.uk/?s=flooding

2.5.5 Clean air

SRCw and *Miscanthus* both produce biogenic volatile organic compounds (BVOCs) from their leaves during growth. These chemicals are produced by a wide variety of plant species globally with emissions from vegetation 10 times higher than those from anthropogenic sources (Szogs, et al., 2017). BVOCs are important as they directly and indirectly influence concentrations and lifetimes of ozone and atmospheric particulates with implications for climate warming. In the case of *Miscanthus*, levels produced are lower or similar to those from oilseed rape, maize and mixed grassland species (Copeland, et al., 2012; Miresmailli, et al., 2013; Morrison, et al., 2016). In contrast, emissions from SRCw have been measured as 1.5 to 300 times higher than *Miscanthus* and arable crops (Copeland, et al., 2012; Morrison, et al., 2016; Hu, et al., 2018). This is consistent with broader understanding that increasing grassland cover globally is predicted to decrease BVOCs, whilst increasing cover of woody bioenergy crops could result in an increase in BVOCs (Szogs, et al., 2017). Crude extrapolations based solely on data gathered from one site in the UK estimate that isoprene emissions from willow could correspond to 0.004–0.03% (UK) and 0.76–5.5% (Europe) of current global isoprene if 50% of all land potentially available for bioenergy crops was planted with willow (Morrison, et al., 2016). This is a very crude estimation and more detailed modelling is needed to predict future changes in BVOCs with increasing energy crop cover, accounting for land use change and climate change impacts on vegetation more broadly.

2.5.6 Wildlife habitats

The evidence indicates that within agricultural landscapes willow SRC, and to a lesser degree *Miscanthus*, have broadly positive impacts on wildlife habitat provision, but this depends on crops being distributed within the landscape, and is potentially sensitive to future changes in land management and the scale of planting (Dauber, et al., 2015; Dauber, et al., 2010; Rowe, et al., 2009; Berkley, et al., 2018; Lesur-Dumoulin, et al., 2018).

Avian, floral and invertebrate diversity and abundance in *Miscanthus* and willow SRC are often reported as higher than or nearly always comparable to arable and improved grassland (Dauber, et al., 2015; Dauber, et al., 2010; Rowe, et al., 2009; Bourke, et al., 2014). Studies of pollinator species in *Miscanthus* have found that whilst overall species richness wasn't greater in *Miscanthus* compared to arable fields, there were differences in relative abundance of different groups (Stanley & Stout, 2013). This is reflected across avian, flora and invertebrates groups, with several studies noting distinctly different species composition within both willow and *Miscanthus* compared to surrounding agricultural land (Dauber, et al., 2010; Haughton, et al., 2016; Rowe, et al., 2009). This is a critical finding as it highlights both that certain species may be negatively affected, including species of national importance such as skylark, but also that positive benefits for wildlife habitat are greatest when these crops are interspersed within the landscape (Guillem, et al., 2015; Rowe, et al., 2009).

Recent work indicates that for *Miscanthus* there is a trade-off between yield and biodiversity (Dauber, et al., 2015). Some older plantations have used suboptimal planting or land preparation, leading to open patches within the fields. These patches support ground flora which, unlike in willow SRC, is absent within the rest of the crop. With *Miscanthus* providing limited direct food value, diversity of invertebrates and seed resources for birds are, at least in part, linked to ground flora, thus are also positively correlated with field patchiness. Whilst it is unlikely to be entirely eradicated, due to failures in planting materials or problem areas of fields, improvements in establishment are likely to decrease patchiness in *Miscanthus*, with potentially negative effects on biodiversity. However, for more mobile species such as mammal and birds, work on hares suggests that whilst dense *Miscanthus* provides limited food resource, within a mixed landscape it can be beneficial by providing shelter (Petrovan, et al., 2017).

Recommendations from the literature include: an assessment of the risks to wildlife provision as an essential part of the planning of bioenergy crop expansion; and the continued prevention of bioenergy planting on priority habitats, such as lowland meadow, bogs, ancient woodland and SSSI's.

2.5.7 Landscape, tourism and rural heritage

Societal responses to perennial bioenergy crops within the landscape are diverse and can be both positive and negative (van der Horst & Evans, 2010; Boll, et al., 2014). The perceived impact of bioenergy crops on recreational use of the countryside was found to be in part location-specific, with higher societal acceptance in Germany for planting on grassland compared to heathland or forested areas (Boll, et al., 2014). The views of farmers and NGOs to bioenergy planting in Yorkshire, highlights the need for clear information about the wider ecological and economic performance of the crops, but also the prevalence of views in NGO's that whilst local use of biomass is "good", commercial use is less supported (van der Horst & Evans, 2010).

2.6 Current challenges and barriers to production

A number of potential barriers to increased energy crop deployment and utilisation have been identified, predominantly from stakeholder interviews. A number of issues around policy are outside the scope of this project, though for stakeholders the presence of a long term, stable policy supporting bioenergy production can be a significant pull in the decision for a farmer to adopt an energy crop and an end user to consider it. All stakeholders considered that any future strategy for innovation and policy development should take a "Beginning to End" approach and include all actors in the supply chain. Getting farmers on board and raising their confidence in energy crops is essential, as is assuring that the middle processing, service supply and logistics companies are included, as well as the final end users of the biomass.

The challenges identified have been grouped into four broad themes: agronomic; technical; economic and market security; and social and non-technical, each of which is discussed below.

2.6.1 Agronomic

This covers the lifecycle management of the crop from initial preparation in year -1, through to harvest, and also through field reversion and up to next crop or replanting.

2.6.1.1 General agronomic considerations

If the UK wants to achieve over one million hectares of dedicated energy crop plantation by 2035 then significant investment will be required: in land, propagation material, processing systems, propagation storage and logistics, planting machines, management practices, harvesting machines, storage and logistics of produced energy crop biomass, and the training and sourcing of a skilled and supportive workforce to provide all the tasks required. The final thing which is required is a long-term end use, with security to provide confidence to producers for contracts for ten or more years (Croxton, 2014; Stakeholder, 2019).

2.6.1.1.1 Access to independent agronomic advice

One of the most frequent statements collected from almost all of the stakeholder interviews was the fact there are not sufficient numbers of trained agronomists with experience in energy crops, and that available information on pesticides application, fertiliser applications, and general plantation management questions is not available or up to date, with most literature now more than five years out of date (Stakeholder, 2019).

Much of the information sought by farmers on best agronomic practice comes from agronomists employed by large supply companies (seed, fertiliser, pesticide etc.). For these suppliers, there is little interest in promoting energy crops, as there is only limited demand for their products after the initial establishment, and so the advice received by farmers may be heavily biased towards annual crops (Stakeholder, 2019). Where advice on energy crops is available, it tends to come from work commissioned by breeders and developers – so can be biased the other way. Independent advice and research are lacking (Stakeholder, 2019).

Stakeholders also raised concerns that the energy crop industry in the UK was highly fragmented, and often at odds with itself. Historically, SRC and *Miscanthus* were seen to be competing options and their benefits were compared against each other rather than non-energy crops, with SRC seen as basically forestry, and *Miscanthus* as only a grass. In effect, this created lots of negative publicity which confused the farmer and everybody else who wasn't directly associated with the industry. In reality, all energy crops have a place, and different crops suit certain situations and growing conditions better than others and it is essentially down to farmer choice across most of the UK. The development of a National Energy Crop Centre, or similar is a service that a number of stakeholders raised in their interview as an innovation they would like to see developed to help overcome a lot of the challenges highlighted in this section (Stakeholder, 2019).

2.6.1.1.2 Improved assessment of plantation viability

One of the biggest challenges raised in establishing energy crops historically has been finding suitable land to plant. Field location and suitability are essential when planning the initial assessment of the area considering to be planted in to energy crops. Field access, size of area to be planted, soil quality and history are the first questions and challenges that the grower needs to consider, as many locations can be found unsuitable at the very early stage. Good initial planning well in advance is essential in assuring a successful plantation, but the information needed to identify the critical factors is limited (Stakeholder, 2019). Better tools for yield prediction, based on field-specific soil information, are also needed (Richter, et al., 2016).

Much of the marketing around energy crops has focused on the potential to use them on marginal land, but this may impact significantly on achievable yield and the harvesting cost. Marginal land is typically unused because it is challenging to use. To understand the potential for energy crops on marginal land will require commercial scale trials to be performed and replicated to gain a better understanding of the opportunity.

2.6.1.1.3 Pesticide availability and suitability

The list of pesticides approved for use on energy crops is limited and in many cases there are no approved pest control methods at key steps in the establishment process. For example: conversion from permanent grass, or arable fields with grass patches, to energy crops, comes with a high risk of soil based insect pest attack, particularly from infestations of leatherjackets (*Tipula spp*), which are the larvae of the Crane fly (Daddy long legs) and/or infestations of wireworm (*Agriotes sputator*) which are the larvae of the Click beetle, for which there are no approved insecticide control methods available. A break crop (a crop of a different species to interrupt the lifecycle of pests/diseases) may therefore be needed before planting, further delaying energy crop planting and increasing costs, both economically and environmentally. While there are currently a small number of post-emergent herbicides approved for weed control in *Miscanthus* under the Extension of Authorisation for Minor Use (EAMU) scheme, the list of available products for weed control is reducing all the time for all energy crops (Stakeholder, 2019).

One of the biggest potential challenges going in to the future from a pesticide perspective is the risk of losing total herbicide, active ingredient glyphosate. Glyphosate is widely used in energy crops in year -1 when preparing initial seedbed for ploughing and planting and again at the end of the first year of planting to kill back competing weeds whilst the energy crop is dormant, and potentially in high weed situations also at the end of the second year of growth. Likewise, it is currently used at the end of life, or reversion stage, when plantations are needing to be removed or replaced. If glyphosate is removed as a potential total herbicide, finding alternative options for this, via organic removal of weeds and development of interrow weeding systems may be the only future option (Stakeholder, 2019).

2.6.1.1.4 Correct storage of planting material

SRC and *Miscanthus* propagation material is produced over the winter months (when the plant is dormant), and so requires chilling and keeping moist until planting in March – June. Drying out of SRC cuttings/rods or *Miscanthus* rhizomes is detrimental to future health and vigour in the establishment phase of planting. Having adequate storage/reception facilities, which are cold storage based (3-6C) for storage of prepared planting material is therefore essential. (Stakeholder, 2019) (Croxton, 2014).

2.6.1.1.5 Availability of suitable planting and harvesting equipment

Planting equipment is typically hired from the energy crop propagation suppliers and harvesting equipment is owned by contractors who operate their equipment on a number of different crops (Stakeholder, 2019). While appropriate planters, forage harvesters etc., or contractors with this equipment, are available to hire, the numbers of equipment items are currently limited, with only a handful of “Step” planters being available for SRC planting across the UK, and these can often be difficult to hire in a busy spring. While an increased market demand should prompt the expansion of available equipment, hire companies will need confidence in the certainty of use before making this investment. It should be noted that use of manual hand planting machines for SRC or *Miscanthus* is also not perfect, compared to automated systems, as mistakes can still be made. Blockages, or lack of concentration by workers, can all lead to gaps and parts of field not being planted evenly or well-spaced. With this in mind, development of new planting systems, automated, and faster, would enable more area to be established within a growing season (Stakeholder, 2019). Should a large scale expansion in energy crop areas be seen, or required, then the availability of contractor services may also be a limiting factor, particularly where the planting and harvest windows may be limited due to weather, new growth, and the fact that contractors are required to be preparing land, planting land, and also harvesting other established crops at the same time of year (Stakeholder, 2019).

As with planting equipment, the supply of harvest equipment suitable for energy crops in the UK is currently limited. While market demand should increase supply as necessary, at present the contract hire companies are maximising their return by using a smaller number of machines over a wider harvest period. This can impact on the yield and quality of the harvest, as the optimal harvest window is missed.

2.6.1.1.6 Control of grazing animals

A common establishment complaint from growers is that deer or rabbits have been grazing newly planted crops, and unprotected parts of fields may be cleared within weeks of new shoots establishing. Identifying large mammal pest risk prior to planting is important when assessing the field location and site risks, and if necessary, the risk can be reduced by using temporary fencing. However, this can add substantively to initial year 0 costs (see Section 2.3). A potentially cheaper alternative to fencing is the use of certain deterrents which are strong-smelling to rabbits and deer but cannot be smelt by humans. These have been tested but require further investigation and evaluation. (Stakeholder, 2019).

2.6.1.1.7 Incorporation of energy crops into farm cycle

Because the establishment of energy crops takes place in the spring, they do not fit neatly into the usual September to August farming cycle which many UK farms follow, meaning the decision to establish an energy crop cannot be a last-minute decision but must be planned in advance. The decision to plant an energy crop must be made 6 -12 months in advance of the proposed planting date, so that the ground can be kept clear of any autumn sown crops and then suitably prepared. This 6 to 12 month window is also needed to agree any end user contracts, and to allow for pre-ordering of any planting material needing to be assured that it will be in place at the time of planting (Stakeholder, 2019).

2.6.1.1.8 Impact of energy crops on soil quality (compaction)

The long-term impacts of energy crops on soil quality, particularly in relation to compaction, water retention, and water run-off, need to be better understood, particularly when it comes to energy crop removal and return to an arable rotation (Stakeholder, 2019). Field compaction in energy crops can become a big issue if harvesting SRC in wet ground conditions where large ruts can be created from the large heavy machinery. Likewise, for *Miscanthus*, regularly running over the same area of crop with tractors causes soil compaction pans, significantly reducing harvestable yields in the future from that area (Stakeholder, 2019).

2.6.1.1.9 Optimisation of harvest cycles

Better understanding is needed regarding potential yields that could be achieved from different harvesting cycles, such as moving to a 2- or 3-year harvest cycle for *Miscanthus,* and a shorter two-year cycle for SRC. If thinking about pushing SRC out to 4 year harvest cycle, then this can create a bigger problem in increased stem diameter, meaning standard modified forager harvesting systems are likely to struggle with cutting larger stems, so changes in harvest cycle would likely be to reduce the harvest cycle from 3 years interval rather than to extend them, but this requires further evaluation and development of suitable varieties, and or harvesting systems to cope with larger stems. (Stakeholder, 2019). There is very little information available on harvesting multiple (rather than single years) growth for *Miscanthus*, and this could be a useful management tool on smaller parcels of land in difficult growing conditions or when weather conditions have not enabled a timely harvest to occur (Croxton, 2015; Stakeholder, 2019).

2.6.1.2 SRC

2.6.1.2.1 Availability of planting material

As with *Miscanthus*, ramping up UK SRC propagation stock to start planting large areas of crop will require significant investment in land, equipment, and people and at least ten years in advance of any expected large market demand targets for planting, unless the UK wants to continue to import material from countries like Sweden (Stakeholder, 2019).

2.6.1.2.2 Development of disease resistant varieties

In certain high yielding varieties, disease resistance or a breakdown of the willow variety to a disease, like rust, can be costly to yield within that harvest cycle. In some instances, trying to control the disease may mean there is no alternative but to take an earlier than planned harvest, seeing a reduced yield. Insect infestations can also impact on certain varieties of SRC willow, and levels do need to be monitored. Application of an insecticide is not common practice, but if pest numbers break thresholds then spraying the crop may be the only way to help prevent yield loss within the cycle. New varieties of SRC are not being developed as regularly as they were in the past due to lack of demand for new planting material. (Stakeholder, 2019). In particular there is a need for further development of rust resistant poplar and willow varieties (Bunzel, et al., 2014).

2.6.1.2.3 Development of automated planting equipment

Planting large areas of SRC in the UK would be a challenge at the present time, as there are currently only five “Step” planters available for hire in the UK (Stakeholder, 2019). So significant development in robotic or automated planting systems is required, which will also reduce or eliminate the risk of planting gaps which can be a problem with manual hand planting systems. Gaps can occur in plantings if the planter loses concentration or incurs a problem with the machine and the problem isn’t noticed quickly. Significant gaps lead to weed build up within a plantation and can require gap filling if cost effective to do so.

2.6.1.2.4 Harvesting systems

Harvesting systems have not been reviewed and updated since the mid 1990’s and are in need of research and development in order to improve extraction efficiency and give the throughput needed for large commercial scale production. (Stakeholder, 2019). The current use of large self-propelled forage harvester systems means that harvesting can occur more quickly than the traditional tractor and trailed mower style systems used historically, which is important if field conditions are changeable in wet conditions. However, this also means that harvesting equipment has become heavier over time, and so can cause more soil damage (ruts) in difficult soil conditions. In addition, the cutting of the stem may not always be so clean and sharp when compared to the mower due to the technique of the “header” cutting system implemented by the forage harvester system. The move from trailed harvester systems also meant the remaining stem heights typically increased, leading to a loss of yield, as the wider cutting head, operated on a forage harvester, can mean more stem needs to be left behind to ensure the cutting head does not touch the ground in uneven situations as it is considerably wider than a trailed mower. Developments in modern harvesting systems could deliver benefits from higher collectable yields, less stump damage/losses from damaged or poorly harvested stems, and less soil/field damage from heavy harvesting equipment.

2.6.1.3 *Miscanthus* planting

2.6.1.3.1 Access to suitable cultivars

Most of the *Miscanthus* currently grown in the UK is *Miscanthus giganteus*. Other cultivars have been identified in other countries, but access to these in the UK is limited. There has been no proper evaluation of these cultivars to determine their suitability for use in the UK, but they may offer, for example, better frost and drought tolerance than *Mx giganteus* (Stakeholder, 2019).

2.6.1.3.2 Availability of planting material

For *Miscanthus*, one of the main concerns often raised is the availability of parent material. While, (Atkinson, 2009) suggests that planting rates would have to rapidly increase for this to be a significant issue, the UK supply of *Miscanthus* rhizome has likely decreased since this assessment. In particular, many of the current *Miscanthus* plantations are unsuitable for use for rhizome propagation, for reasons of age, or because extraction from the soil would be technically or economically unfeasible. The assessment was also based on meeting a lower overall target for planted land area under the original Energy Crops Schemes, where the target was 125,000 hectares. A Defra project report on energy crops suggests using rhizome-based propagation, where expansion of the planted area is relatively slow, due to the rhizome harvesting of one hectare only providing enough material for around three hectares (NIAB, 2007). However, stakeholders with commercial scale experience have indicated that this is a very pessimistic estimate when using dedicated rhizome nursery plantations, with current commercial multiplication rates requiring approximately one hectare of propagation material, growing for 3 years, to plant fifteen hectares for long term biomass use being readily achievable (Croxton, 2014). However, there is still only a very small area of nursery plantation area in the UK as of 2019, so this area of rhizome propagation material would need to be increased before large areas of miscanthus could be established for longer term planting of biomass production (Stakeholder, 2019).

Vegetative propagation is an alternative to rhizome use, but the systems to undertake this are not readily available in the UK (Stakeholder, 2019).

2.6.1.3.3 Automation of planting

Rhizome pieces are uneven in size and shape, which can cause problems with automatic planting systems. Generally, hand planting is more effective at better rhizome placement, and when only planting lower numbers of hectares per year. I.e. less than 500 hectares. However, if *Miscanthus* planting is to increase to a level where thousands of hectares a year are required to be planted, within a 3-month spring planting window, then speed and automation will be needed, as will an adequate resource of propagation material. (Stakeholder, 2019).

Seed based hybrids have been developed and are being trialled and have shown some good chemical characteristics in small scale trials to date, although field survival is improved through germination and plantlet formation via nursery propagation (which would negatively impact GHG emissions and increase costs compared to direct sowing) (Hastings, et al., 2017), it has not yet been proven on a commercial scale. While there have been successful trials in the direct sowing of *Miscanthus* seeds (Clifton-Brown, et al., 2017), further optimisation of the systems used would be needed before it can also be commercially available. It is likely that seed-based varieties will always require an additional processing step to a plantlet stage before planting can occur (Stakeholder, 2019).

2.6.1.3.4 Cost of planting material

Rhizome costs for *Miscanthus giganteus* are well established and available, but the new varieties being developed (such as for growth from seed) may attract a royalty charge payable to the developer, which could increase the costs to the farmer from this system in the future.

Plantlet-grown *Miscanthus* is currently more costly than rhizome production but may be required for supporting a high intensity planting effort (Atkinson, 2009). At present, there are also insufficient nurseries able to offer the large-scale commercial operation for developing plantlet-grown *Miscanthus*. (Stakeholder, 2019).

2.6.1.3.5 Maximising biomass recovery through use of leaves

For *Miscanthus* in particular, the highest potential biomass yields are seen just before senescence but harvesting of the crop at this point is rarely done mainly due to the high moisture content at this point. *Miscanthus* is therefore generally harvested following its senescence, when the moisture content in the canes is reduced. However, by this time the leaves have dropped and are generally not recovered, so do not form part of the overall achievable yield. The fallen leaves do however create a natural mulch, providing some weed control, helping the canopy to retain moisture content and over time will provide some low-level nutrient back to the growing crop.

While these uncollected leaves represent significant yield loss, their chemical composition (and contamination with soil) can make them unsuitable for use in a combustion plant. In particular, the high silica content was identified as being problematic when used in combustion, though options such as washing have not been thoroughly explored to counteract this and potentially remove the barrier of not collecting the leaves. (Croxton, 2019). This may be less of an issue with non-combustion conversion technologies, but there has been only limited exploration of these options with *Miscanthus,* and nothing was found in the published literature.

2.6.1.3.6 Invasive characteristics of *Miscanthus*

One advantage of using *Miscanthus giganteus* is that it is a sterile triploid hybrid, hence it can only be spread by deliberate use of rhizome or propagule planting material. A move to seed planted varieties may increase the risk of invasiveness; although *Miscanthus* would not typically flower in a UK climate, (sterile) flower heads have been formed in UK *giganteus* plantations in a handful of years. With fertile varieties, a single seed head can contain thousands of seeds, and the height of *Miscanthus* would help these spread over a wide area. With a warming climate, years where *Miscanthus* can flower in the UK may become more common (Stakeholder, 2019). However, there is no information on how probable this is.

2.6.2 Technical

2.6.2.1 Densification for storage and transport

Cost effective storage and transportation of energy crop biomass remains an issue. SRC chip and indoor/covered *Miscanthus* bale storage is expensive because of the relatively low bulk density and the dry matter losses incurred; there is also a self-heating risk. An alternative for longer term storage and more efficient transport logistics is to pelletise, but this incurs significant energy penalties, and so may only be cost effective when storage is over longer periods or where longer distance transport is required (Sahoo, et al., 2018). End user off-take contracts often contain a bonus if the material is stored on-site until required by the end-user, (e.g. Terravesta for *Miscanthus*), but this may result in overall lower sales by the farmer due to dry matter losses, as well as taking up storage space that may be needed by other crops. On-farm pelletisation is not really feasible currently, as existing commercial size systems require tonnages greater than 5,000 tonnes/year, which is about 500ha of planted energy crops; so regional level densification facilities would therefore likely be required, and should be more cost effective than farm-based systems.

2.6.2.2 Optimisation of material drying

For many conversion processes, dry feedstock is needed to give the highest efficiency. For example pelleting of energy crops requires feedstocks to have a low moisture content so that they can be ground down/milled. While delaying *Miscanthus* harvest until after senescence can significantly reduce the moisture content, additional drying may be needed. For SRC, moisture levels in fresh-cut material are usually significant, of the order of 50-60%. Drying can be natural, either in the field (which may require a two-stage harvest system with cut material left before chipping) or at a central collection point, or forced drying with low-grade heat and/or forced ventilation in storage can be used (Schweier & Becker, 2013). A better understanding of the costs and impacts (on greenhouse gas emissions and characteristics and quality of the material) of these different drying systems in large-scale energy crop production would improve optimisation of this step.

2.6.2.3 Crop monitoring

When a plantation is growing, physically being able to see if anything is going wrong with it from a disease, or pest attack perspective is almost impossible from simply walking amongst the crop, unless you happen to be lucky or the infestation is so great it has already affected all of the crop. If crops could be monitored from above more easily, then early spotting of potential high-risk areas could enable early treatment of crops to avoid cycles being lost or seeing a diminished yield. Development of remote sensing and satellite (and/or drone) image analysis systems to better estimate crop cover and productivity and so inform productivity forecasts would therefore be beneficial (Ahamed, et al., 2011; Richter, et al., 2016). This can also be used to identify issues such as nutrient deficiency, which is difficult from the ground to spot in such tall crops.

2.6.2.4 Material optimisation for different end-use markets

The majority of energy crops are currently targeted towards large scale combustion, with smaller scale combustion systems being generally designed for white wood pellet or chip from forestry sources rather than energy crops. Better understanding of fuel quality demands of small-scale biomass systems and the impact of energy crops on these (Sinclair, et al., 2015) is needed to identify what changes are needed to give access to these markets. In some cases, pre-treatment of crops e.g. by washing, sieving etc. may be justified if the crop can be upgraded to be suitable for higher value applications.

2.6.3 Economic and market factors

2.6.3.1 Mitigation of liquidity risks

In many areas, the production of energy crops will be competing with other land uses, particularly arable crops, but also pasture, forestry and potentially housing. Perennial energy crops have long latency between the initial (significant) expenditure to prepare and plant the area and the first harvest income (two to four years, compared with less than a year for many arable crops), and so the landowner needs sufficient liquidity to survive this period. In addition, for SRC crops the landowner needs to be able to cover the non-harvest, no income years, which may be two out of every three years, throughout the lifetime of the crop (Bocquého & Jacquet, 2010). Market confidence in energy crops in the UK is low, in part due to previous project failures. Obtaining the necessary financing for future market development and propagation material for large scale establishment may therefore be challenging. While food prices can be highly volatile year-to-year, the lower establishment cost and the potential of higher profit from an annual crop can seem to be lower risk than energy crops, unless risk mitigation options such as subsidy/planting grants or a guaranteed off-take price for the biomass is available. Farmers also do not have to agree to multi-year contracts for annual crops, but for energy crops contracts are typically 10 or 14 years long, with break clauses usually being quite far apart in years, which removes the flexibility that farmers have when growing annual crops. For example, in a normal farming situation, if the price for wheat suddenly increases to more than £200/t, then farmers can manipulate their farm rotation to plant more wheat to sell at a higher price and meet market demands. This is not achievable with a long-term energy crops planting and so the latter requires a different business approach and mindset (Stakeholder, 2019).

2.6.3.2 Secondary impact on farm costs

Except where under-utilised land is converted to energy crops, or extra land is rented, increasing the area of energy crops within a farm will reduce the area available for other crops. However, many of the costs associated with arable farming, including equipment purchase and full-time labour employment, are fixed costs to the farm business, so the cost per hectare of production will increase across the farm, therefore making margins on high value crops lower (Stakeholder, 2019). For example a tractor would be used several times during the year on land where annual arable crops are grown but only at the beginning and end of the plantations life (20 years later) on land where energy crops are grown. So in farm where some where some of the area is diverted to energy crops, the cost of that tractor must be written off across a smaller area.

2.6.3.3 Better cooperation and planning between supply and demand actors

Most unprocessed energy crops (in either chip or baled form) have a low bulk density (typically 90 – 165kg/$m^{3)}$ so current supply chains usually target a local market for the off-take, or transport costs which are relatively high due to the low bulk density are likely to start to impact on profit. This would favour the development of small-scale conversion systems, taking feedstock from a limited radius. However, there is a chicken and egg situation, whereby conversion plants need a guaranteed fuel supply to be installed before building, while energy crop growers need certainty of use before they will establish a crop (Alexander, et al., 2013). As a result, dedicated bioenergy plants have generally opted to base boiler designs and fuel supply logistics around more widely available feedstocks such as wood pellet/chip and waste wood. Smaller conversion plant also tend to be located closer to population centres (as supplying heat as well as power requires customers), which typically have higher land prices and so require a high value crop to compensate (Abolina, et al., 2014). Where land is rented, considerations over tenancy length and the permission from the land owner to grow energy crops also have an influence on the decision, and capability to succeed (Stakeholder, 2019).

2.6.3.4 Commercial demonstration on a wider variety of land types

The decision to plant an energy crop will require the grower to expect a profit; for this, an expected yield (and price) is required over the length of the supply contract. Understanding what process steps are likely to be required for a certain field or farm location can also be variable depending on which source is used as a reference, as discussed in Section 2.3. A number of models have been developed to try and predict biomass yields based on soil types (Hastings, et al., 2009; Alexander, et al., 2014), but comparison of theoretical and actual yields can show large variations, particularly for heavy soils (Richter, et al., 2016). This could disincentivise expansion of energy crop areas from initial test areas. Demonstration plantings on a wide range of soil types at a larger commercial scale than the small scale trials carried out to date, could help with grower confidence in the longer-term achievable yields in different regions and on different soil types (Stakeholder, 2019).

2.6.3.5 Lack of end use markets for produced biomass

At present, there is only one large scale commercial scale market for energy crops – combustion plant. This means that growers are limited in who their potential end use customers are, and in some cases have no certainty of use for the 20+ years of the crop's lifetime. Diversification of energy crops into other end uses (energy and non-energy) would help to provide a more stable market and potentially provide higher prices for the harvested material (Stakeholder, 2019).

2.6.3.6 No additional support for local feedstock use in new plant

Renewable energy subsidies no longer support the development of new conversion plant designed for biomass, and particularly energy crops. Instead, it is more economic to convert existing plant and use "easier" (usually imported) feedstocks such as white wood pellet. As a consequence, plant are not being built to provide a market demand for energy crops (Stakeholder, 2019).

2.6.4 Social factors

Social factors are outside the scope of the study so were not searched for during the literature review. However, several stakeholders identified social factors as one of the barriers to expanding energy crop production and their views are summarised below.

One potential barrier to the deployment of energy crops may be the attitude and experience of the farmer. Some may be particularly risk adverse and so be unwilling to try a new crop, particularly one that takes three years to produce a harvest and 20+ years for a complete rotational cycle. This means that the grower is unable to react to changes in market conditions and switch to higher value products without losing some of the investment made in the energy crops (Stakeholder, 2019).

While the idea of a very low maintenance crop appeals to some growers, particularly if it is on previously under-utilised land, it may be a frustration to those who are accustomed to more active management. The median age of UK farmers is high, at 60 (DEFRA, 2018), and they have been conditioned towards the growth of (subsidised) food crops and so changing to energy crops would require a substantial change in mindset (Stakeholder, 2019). Even among younger farmers, many farms are diversifying to cater to the current social trend of eating locally sourced food, which may offer increased profit and challenge when compared to farming energy crops.

One of the major problems historically has been people or companies who advise and support the farmer with business or cropping decisions, have not always been informed about energy crops, or have had a bad experience with it, maybe have heard about someone else who had a bad experience of it, or have a vested interest to not inform the farmer (for example the vested interest may be a potential to lose long term future income). Putting this in to perspective, if the farmer doesn't need to purchase as much fertiliser or pesticide in the future due to growing more energy crops, then it is probably not realistic to think he will be advised by a business which is selling him these products to grow an energy crop (Stakeholder, 2019). Those who influence farmers decisions, such as agronomists, accountants, land agents, farm service suppliers, also all need to be informed and convinced of the benefits of energy crops. There is also a need to identify earnings opportunities from energy crops for these sectors, otherwise there is a risk they could lose income if more of their farmer customers decide to grow areas of energy crops (Croxton, 2014).

In some areas there may also be a "not in my backyard" attitude from neighbouring land users which can create opposition to the land use change.

The use of field margins as a planting area for energy crops, to enhance on farm biodiversity and work as nutrient management or capture zones, (with the energy crops acting as a buffer between different crops, or crops and water courses) has previously been proposed. However, this approach could be difficult on some sites due to the presence of existing hedgerows or the need to ensure that the energy crop (which can be up to 4 m high) would not encroach on or impede progress on any existing footpaths. On sites where it is possible, these smaller areas of land are technically difficult to manage and perform operations on. Consequently, they are more expensive to harvest than large fields and may therefore be less profitable. Some growers who have investigated this route in the past have found that achieving Environment Agency approval for utilising such parcels of land has proven to be very difficult (Stakeholder, 2019).

One of the more sensitive points raised by stakeholder interviews was the consideration of GM or GE technology use to be re-evaluated for the use in energy crop development. Energy crop material is not going to end up in food production, and these technologies can be used to accelerate breeding. There is also the potential for these techniques to enable energy crops to create some interesting chemical compositional opportunities, for example drug pre-cursors, for the industry to develop and produce into the future and so provide a very high value side product from bioenergy production (Stakeholder, 2019).

Finally it is suggested that improved recognition of non-energy benefits of energy crops and a way to ensure inclusion of these in any assessment of energy crops planting could encourage more take-up (Sinclair, et al., 2015)

2.7 Supply chain innovations

This section describes innovations which could accelerate the uptake of energy crops by landowners/land managers. Innovations are focused on breeding, planting materials, on-farm cultivation and processing. These are innovations which address challenges and barriers identified in section 2.6, and are focused solely on technical innovations which improve yields/productivity, economic return and wider environmental or societal benefits. Innovations are broken down into the steps within the supply chain and also describe innovations that encompass the whole cultivation process. The innovations identified through the literature review and stakeholder consultation fall into six categories: (1) breeding and propagation of planting materials; (2) agronomic innovations in planting and establishment; (3) agronomic innovations in crop management; (4) harvesting and processing innovation; (5) agronomic innovation in alternative uses of energy crops (6) land use innovation to harness the environmental benefits of energy crops; and (7) innovations in information supply and engagement to address barriers to uptake

Each section comprises a summary of evidence from the literature review combined with expert opinions of the project team and a summary of responses from the stakeholder consultations. Where there is duplication between innovations identified in the literature review and the stakeholder consultation, only additional points from stakeholders are listed. Where appropriate, evidence is described separately for *Miscanthus* and SRC but combined in some sections.

2.7.1 Breeding and propagation of planting materials

2.7.1.1 SRC

An extensive multi-author review with industry and academic authorship recently summarised the current state-of-the-art in SRC willow and poplar breeding, propagation and scaling-up, and the recommendations and innovations proposed in this review are summarised below (Clifton-Brown, et al., 2018).

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. In 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). A range of varieties has been developed through breeding 2004-2011 (700 crosses) and tested for a range of traits including yield, pest and disease resistance and climate resilience (drought tolerance) (Stakeholder, 2019). 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.

There is huge genetic diversity in willow SRC which could be harnessed for genetic improvement but 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 described 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). Breeding technologies which have potential to make significant gains in SRCw include marker assisted selection (MAS) which uses marker sequences for traits to allow early progeny selection; and genomic prediction and selection (GS) which can

accelerate breeding through reducing the resources for cross attempts (not attempted yet for SRCw) (Clifton-Brown, et al., 2018).

- 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 which crops could be exposed to under future climate scenarios.
- Flood tolerance (inundation tolerance and resilience to water flow) is a significant knowledge gap. While some assessment can be made from how existing plantations which have been flooded have fared, there has been no systematic breeding or screening of current varieties to maximise flood resilience and mitigation. This would be needed if in the longer term energy crops were to be more widely planted on flood plains in the future, helping to maximise the range of conditions and areas in which they can successfully be established. . 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 system where existing plantations can be used as nurseries to supply willow rods on a region by region basis rather than importing willow rods from Europe. This will lower costs and GHGs.
- 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.

2.7.1.2 *Miscanthus*

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 which has ~1:15 multiplication rates after 3 years (Clifton-Brown, et al., 2017; Clifton-Brown, et al., 2018; Lewandowski, et al., 2016; Hastings, et al., 2017; Xue, et al., 2015).

Innovation in this area is focused on a range of short- and medium-term objectives, but overall innovations proposed in the literature 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 the 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™) (Xue, et al., 2015).

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/lower energy extraction.
- 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.

2.7.2 Agronomic innovations in planting and establishment

This section focuses on innovations in land preparation, planting strategies and establishment phase management.

2.7.2.1 SRC

2.7.2.1.1 Weed control

Weed control has been identified as a critical factor in successful establishment, with the effects of different chemical and mechanical weeding strategies on productivity reported in a number of studies (Larsen, et al., 2014; Albertsson, et al., 2016). Weed control is currently heavily reliant on pesticides, 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).

2.7.2.1.2 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. These could be achieved by innovating to improve current designs. 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). Similar planting methods have also been developed with a comparison of planting methods and alternative horizontal planters reported (Larsen, et al., 2014; Manzone, et al., 2017). 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) in Appendix 1).

Other areas for innovation include: (1) determining optimal planting densities/ row spacing and how this varies with different varieties/clones/morphologies which could guide machinery innovation (Larsen, et al., 2019); and (2) 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.).

2.7.2.1.3 Other innovations

Stakeholders expressed the view that there is inertia in the industry regarding the development of new machinery for planting and harvesting due to the large investments in existing kit and the relatively small number of growers requiring the service of contractors at infrequent intervals. However, it was stated 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 by stakeholders was to develop strategies for planting energy crops at different (non-spring) times of the year. For example, 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 need to be developed by Natural England e.g. low till planting to reduce soil disturbance and soil carbon loss.

2.7.2.2 *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.
- Joint development of agronomic machinery for planting and harvesting in tandem with testing of different varieties and traits to determine the optimal combinations of plant morphology, planting density, crop management, harvest time and harvest machinery which can together deliver the greatest yields and production efficiencies whilst minimising GHG emissions.

2.7.3 Agronomic innovation in crop management

2.7.3.1 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 will 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 which 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 addition, strategies to harvest fields in stages have been developed to account for variable moisture contents within a field. In SRCw, similar studies have been conducted which have demonstrated that harvest cycle affects both yield and biomass quality with significant differences between five new cultivars tested (Stolarski, et al., 2011). For both crops, this information needs to be incorporated into agronomic protocols of best practice for new cultivars.

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

2.7.3.2 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[11]

2.7.3.3 Crop removal or re-planting

End of life crop removal strategies need further research and testing as whilst successful removal of commercial plantations of both willow SRC and *Miscanthus* has been undertaken in the UK, research on the economic and environmental impacts is limited, 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 C 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.

2.7.4 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).

2.7.4.1 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). There is experience from the Swedish study reported in Appendix 1 describing the development of cutting heads and harvesting techniques which should be examined for its application to the UK context.

Harvest machinery requirements will vary depending on rotation length. This has been explored with SRC poplar but the interactions between harvest time, rotation length and machinery requirements

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

needs considering in any future innovation (Santangelo, et al., 2015). Research on the effects of harvest intervals on yield which could 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). A need was also identified to design, test 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 This 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 (see Appendix A).
- Harvesting windows are currently very wide to accommodate the fact that there are only a few contractors with harvesting machinery, and they want to get best value out of their investments. Harvesting outside of the winter dormant window may reduce yield, overall plantation life and reduce fuel quality. The consequences for yield of variable harvest time-points need further testing through trials or accessing data from commercial farms and potentially modelling.

2.7.4.2 *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). Studies have shown harvesting techniques, climatic conditions and plant morphology interacting to affect biomass yield and quality (Lewandowski, et al., 2016) and there are a range of trade-offs which need further research and development. 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.

2.7.4.3 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.

2.7.4.4 Biomass storage

Biomass storage can have a significant influence on the economics of energy crop cultivation (Sahoo, et al., 2018). 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, which does not include the use of having to place large sheets over the top of stacks, which is a significant health and safety risk, was also suggested. (Stakeholder, 2019)

2.7.5 Agronomic innovation in alternative uses of energy crops

There is a need to extract higher value from energy crops to improve the economic return and so drive uptake. Innovations proposed in stakeholder consultations include:

- Development of alternative future end uses for SRC. For example, high value industrial compounds have been identified from SRCw as well as compounds with pharmaceutical interest and there is great potential for further discoveries. These can be extracted from biomass before the chip goes to conventional bioenergy markets. It is likely the economics that dictate current plantation design and harvest interval will allow plantations for these high value markets to be planted more densely and harvested more regularly, so they may look different to the conventional SRC model.
- Development of alternative future end uses for *Miscanthus*. For example, in materials such as furniture, particle boards, fibre insulation and biorefineries. This will require re-screening of previous and new varieties for a range of traits. High carbohydrates for extraction of industrial sugars for conversion into, for example, plastics; High lignin for materials use; Low lignin for AD use and hence production of compressed natural gas (CNG) for heavy duty vehicle use (increasing demand).
- Development of on-farm alternative products or to enable extension of carbon storage, such as *Miscanthus* use in the development of building materials, and floor tiles.

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

2.7.6.1 Energy crop planting on contaminated or urban land

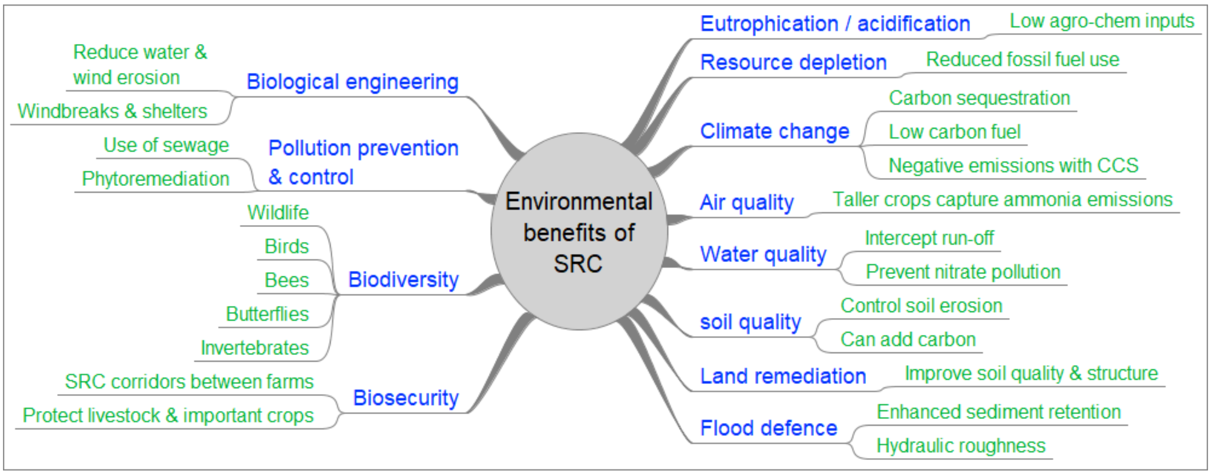
Perennial bioenergy crops including willow SRC, *Miscanthus* and Reed canary grass have potential to be used for phytostabilization, phytodegradation and/or phytoextraction of organic and inorganic pollutants on contaminated or brownfield land with potential environmental and socio-economic benefits delivered alongside the production of bioenergy feedstocks (see section 2.5), but there are significant challenges in achieving economic yields on these sites.

Further research is needed to identify appropriate hybrids/varieties of willow SRC, *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).

2.7.6.2 Multifunctional land use innovations

Producing energy crops on contaminated or urban land or agricultural land which is marginal for food production is likely to be economically challenging if the crops are only valued on their yield. As described in section 2.5, 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 2-16. 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 multifunctional 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 multifunctional value of energy crops can be used as a tool to increase the uptake of energy crops by growers.

Figure 2-16: Summary of the potential multi-functional environmental benefits of Short Rotation Coppice Willow



Source: adapted from (Adams & Lindegaard, 2016)

Data innovation is needed to better understand, assess and value the multifunctional benefits of energy crops in different localities to better inform potential growers (see section 2.5) 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.

Landscape and farm-scale integration of energy crops: The delivery of a range of ecosystem services is affected by energy crop cultivation (see section 2.5). Innovations proposed focus on how multifunctional 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: (1) enable the value of these benefits to be quantified and explained to potential growers; (2) enable this information to be integrated into land use planning at regional, local and farm-scale to increase sustainability; and (3) 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 and Defra understand the package of environmental benefits that energy crops can bring to a farm

Management strategies for specific environmental objectives:

1. 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.

2. 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.

3. Cleaning up contaminated water: 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).

4. Healthy soil:

See section 2.7.6.1 on energy crops and contaminated land.

5. 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.

6. 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, 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 multifunctional 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 2.7.1.1).
- 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.

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

2.7.7.1 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 in the ETI Refining estimates of Land for Biomass report 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)104 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 include:

The need for a national Energy Crop (energy crops) Centre as a central, independent source of information and expertise for farmers/grower focused on energy crops was an idea strongly supported by all stakeholders consulted, where it was viewed as critical to upscaling bioenergy feedstock cultivation. Proposed aspects that the centre should bring together include:

- 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 100,000 ha of energy crop plantings every year, from a standing start in 2022

2.7.7.2 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. There are good examples of this from Sweden (see Appendix 1). 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 view points on bioenergy and biofuels in areas where energy crops could be planted. This needs to include information on the local benefits of large-scale use of biomass, which tends to be viewed more negatively than local use of biomass.

2.7.7.3 Economic innovations

- 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).

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).

2.7.8 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 2-16 summarises the key innovations and identifies the challenges or barriers which they address, and where appropriate an assessment of the potential impacts on the cost of production. Impacts on the cost of production were broadly categorised as high, medium or low based on whether innovations were likely to improve yield, either directly by increasing productivity and harvested yield, or indirectly for example through increased establishment success or expansion of the type of land which can be planted.

Table 2-16: Summary of innovations addressing identified challenges and barriers

Challenge/barrier addressed	Miscanthus or SRC	Innovations	Impact on cost of production
Increasing yield and resilience in new varieties	Misc.	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.	High if bred for yield
	SRC	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.	High if improves yield
Scaling up production of planting materials	Misc.	Cultivars with high seed production for scaling up.	Low
	Misc.	Adapted machinery methods for *Miscanthus* seed production.	Low
	Misc.	Improved propagation methods to reduce costs, increase scalability and improve establishment success.	Low
	Misc.	Improved storage systems and treatments for propagation material.	Low
	Misc.	Improved rhizome production, storage and transportation to maintain vigour.	Low
	SRC	Production sites for planting material need scaling up alongside innovative method development e.g. micropropagation.	Low
Planting machinery innovations to increase establishment success and productivity	Misc.	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.	Medium
	Misc.	Seed-treatments, agronomy and machinery for direct-sowing of *Miscanthus* seed.	Low
	Misc.	Machinery development for automated rhizome planting.	Low
	Misc.	Joint development of agronomic machinery in tandem with novel varieties and agronomic strategies to maximise yield and cost and GHG savings.	High
	SRC	Planting machinery improvements combined with testing of optimal planting densities (variety-specific) and machinery for contaminated/marginal land.	High if improves yield
Increased establishment success and	SRC	Breeding for traits to increase planting success e.g. delayed bud-burst.	Low
	Misc/SRC	Weed control: herbicide-free agronomy, cover crops, machinery development and testing e.g. mechanical and robotic weeders.	Medium

Challenge/barrier addressed	Miscanthus or SRC	Innovations	Impact on cost of production
expansion of planting window	Misc.	Developing strategies to plant at different times of year (non-spring) e.g. autumn planting under plastic to extend the planting window.	Low
	Misc.	Development and testing of soil amendments for marginal or contaminated land.	Low
Development of new pesticides	Misc/SRC	Herbicide development and trials.	Low
	Misc/SRC	Pesticide development and testing combined with new cultivars with pest and disease resistance traits.	Med: frequent use will affect yield
Innovations in harvesting machinery to improve efficiency and access to difficult sites	Misc/SRC	Innovations in cutting blades or heads and speeds to improve yield and reduce costs/GHGs.	High
	Misc/SRC	Development and testing of harvesting machinery with new varieties, harvest times, rotation lengths .	High
	Misc	Baling technology: improvement to increase bale density so reducing costs and evaluation of baling chipped material.	Medium
	SRC	Machinery development for marginal areas (small, wet or sloping sites) and for winter harvesting at wet sites e.g. track-based machinery.	High
	SRC	Development of mobile on-farm pelleting.	Medium
	Misc/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.	
Increasing knowledge on optimal harvesting	Misc/SRC	Research to optimise harvest time or rotation length to maximise yield, nutrient offtake and feedstock combustion quality.	High
	SRC	Breeding for traits to widen the harvesting window including multi-site trials for traits of interest.	Low
	SRC	Information needed on long-term yield effects of harvesting outside the winter dormant window to inform to growers and contractors.	Low
Feedstock storage innovation to ensure feedstock quality	Misc/SRC	Development of optimised storage systems including on-farm storage to maximise feedstock quality and scale-up storage facilities.	Medium

Challenge/barrier addressed	Miscanthus or SRC	Innovations	Impact on cost of production
Monitoring to improve yield and reduce costs	Misc/SRC	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.	High
Concerns over difficulties with crop removal	Misc/SRC	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.	Low
Alternative end-uses to diversify markets and improve economics	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.	Medium
Land use innovation to enable growers to benefit from multifunctional benefits of energy crops	Misc/SRC	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.	
	Misc/SRC	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.	
	Misc/SRC	Develop decision-support tools to inform growers of multifunctional benefits of energy crops in specific locations.	
	Misc/SRC	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.	
	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.	

Challenge/barrier addressed	Miscanthus or SRC	Innovations	Impact on cost of production
Updated guidance for growers	Misc/SRC	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.	
	Misc/SRC	Fertiliser information and trials for micro and macro elements.	
	Misc/SRC	Pesticide register.	
	Misc/SRC	Varieties list.	
Supply of robust, independent Information and advice	Misc/SRC	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.	
	Misc/SRC	Energy crops levy board.	
	Misc/SRC	Development of recommended varieties lists as for other agricultural crops.	
	Misc/SRC	Pesticide register.	
Lack of awareness in key stakeholder groups and public	Misc/SRC	National centre to coordinate engagement with wide range of stakeholders and publics with influence e.g. agrochemical companies, land agents.	
Economic innovations	Misc/SRC	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.	

3 Long rotation forestry

3.1 Introduction

The forest area of the UK fell to a very low level by the start of the 20th century (c. 5%) and although some limited afforestation occurred in the early 1900s, woodland loss was exacerbated by the first World War and was a factor leading to the establishment of the Forestry Commission. Consequently, the initial requirement to develop a strategic reserve of timber encouraged the planting of fast-growing exotic species, which is one of the drivers that over time has resulted in around 69% of the current area of forest being composed of only 8 (principal) species[12]. The current area of woodland in the UK is shown in Table 3-1.

Table 3-1: Area of woodland in UK (as of 31 March 2019)[1]

	England kha	Wales kha	Scotland kha	Northern Ireland[4] kha	Total UK kha
	National forest estate (FC/FLS/NRW/FS)[2]				
Conifers	151	98	428	56	732
Broadleaves[5]	64	19	41	7	131
Total	215	117	469	62	863
	Private sector[3]				
Conifers	189	54	645	11	899
Broadleaves[5]	904	138	343	40	1,426
Total	1,093	192	988	51	2,325
	Total Woodland				
Conifers	340	152	1,072	67	1,631
Broadleaves[5]	968	158	385	46	1,557
Total	**1,308**	**309**	**1,457**	**113**	**3,188**

Source: (Forestry Commission, 2019)

Notes:
1. Figures for England, Wales and Scotland are based on data obtained from the National Forest Inventory and adjusted for new planting, but at present no adjustment is made for woodland recently converted to another land use. All data is provisional.
2. FC: Forestry Commission (England), FLS (Forestry and Land Scotland), NRW: Natural Resources Wales, FS: Forest Service (Northern Ireland). NRW estimates only relate to woodland formerly owned/managed by FC Wales.
3. Private sector: all other woodland. Includes woodland previously owned/managed by the Countryside Council for Wales and the Environment Agency in Wales, other publicly owned woodland (e.g. owned by local authorities) and privately-owned woodland.
4. Figures for Northern Ireland are obtained from the Northern Ireland Woodland Register.
5. Broadleaves include coppice and coppice with standards.

Key points include:

- The area of woodland in the UK at 31 March 2019 is estimated to be 3.19 million hectares. This represents 13% of the total land area in the UK, 10% in England, 15% in Wales, 19% in Scotland and 8% in Northern Ireland.

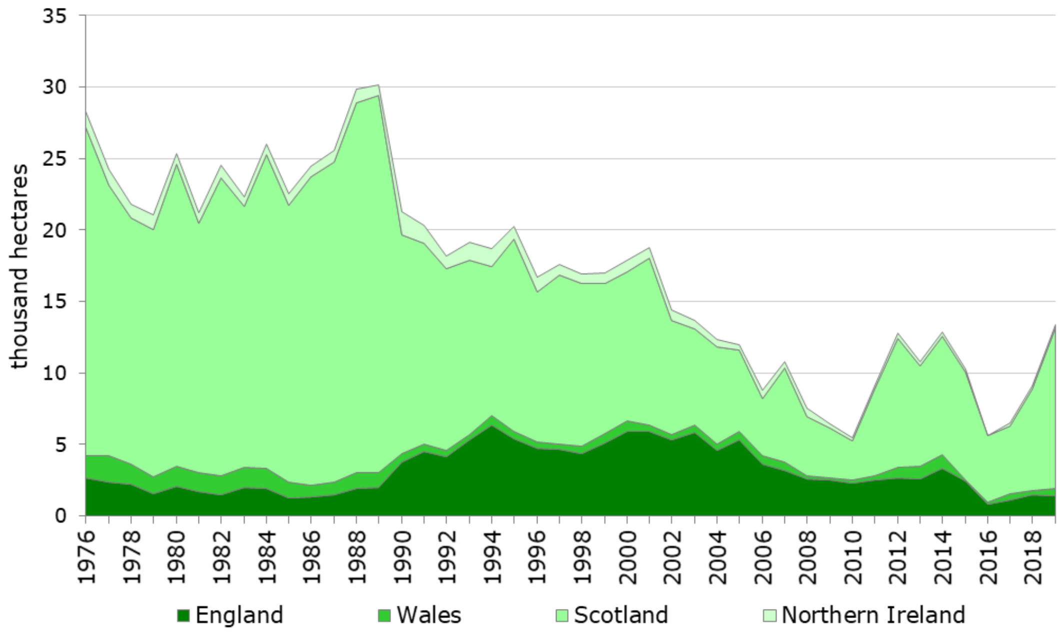
[12] Forestry Statistics 2018. Based on data from the National Forest Inventory. “Principal species” in this context means the dominant species in an area of woodland, it does not mean there are no other tree species present.

- Of the total UK woodland area, 0.86 million hectares (27 % of the total area) is owned or managed by the Forestry Commission (in England), Forestry and Land Scotland, Natural Resources Wales or the Forest Service (in Northern Ireland).
- The total certified woodland area in the UK at 31 March 2019 is 1.40 million hectares, including all Forestry Commission/Forestry and Land Scotland/Natural Resources Wales/Forest Service woodland. Overall, 44% of the UK woodland area is certified.
- Thirteen thousand hectares of newly created woodland were reported in the UK in 2018-19.
- Fifteen thousand hectares of publicly-funded woodland restocking were reported in the UK in 2018-19.
- Conifers account for around one half (51%) of the UK woodland area, although this proportion varies from 26% in England to 74% in Scotland. Although the area of conifers is of the same order in the public and private sectors, there is ten times more broadleaved woodland in private ownership than in the public forest estate.

Trends in planting and restocking over the last four decades are shown in Figure 3-1 and Figure 3-2. The pattern of planting through time influences the age structure of the UK's forests, and the age in conjunction with the species influences when areas are thinned, harvested and replanted.

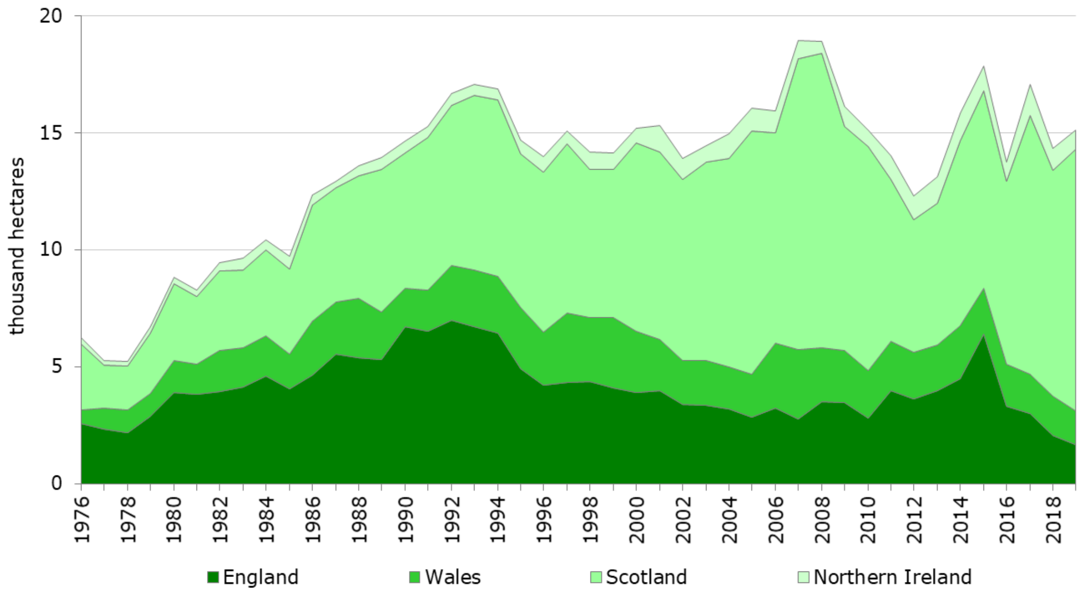
Although the total area of UK woodland has increased consistently over the last twenty years, the annual level of new planting has fallen overall. In particular, publicly funded new planting fell by over 80% between 1988/89 and 2009/10 following changes to the tax benefits in 1988. This drop was initially not observed in England, as the Farm Woodland Scheme, which makes an annual payment where agricultural land has been converted to farm woodlands to defray loss of income, was introduced about the same time as tax benefits were changed. However, from 2004/5 planting levels fell there too, until the introduction of the English Woodland Grant Scheme in 2007. In Scotland, the introduction of Rural Development Contracts in Scotland in 2008 saw the total level there more than double between 2010 and 2012. From then until 2017/18 new plantings were maintained for two years, fell back again, as a result of changes in grant schemes, and finally rose again (by 40%) with the introduction of the Countryside Stewardship scheme. The volatility observed shows how factors such as tax environment and grant schemes can have significant impacts on levels of planting, however they are not the only factors.

Figure 3-1: New planting in the UK from 1976 to 2019



Source: (Forestry Commission, 2019)

Figure 3-2: Restocking in the UK from 1976 to 2019



Source: (Forestry Commission, 2019)

3.2 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) are outlined below for conifer plantations and also broadleaved woodlands where they are managed for economic purposes. They reflect typical current practice for conventional long rotation forestry.

1 **Planting stock preparation**: this is the sourcing of whatever material is to be planted and its preparation to the point that it is ready for planting. 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).

2 **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.

3 **Planting and establishment:** these are those processes directly involved in the planting of the crop. For commercial conifer woodland, the objective is to establish 2,500 – 2,700 seedlings in a square grid pattern. For broadleaved woodland, particularly if there is no commercial objective, wider spacing is acceptable. This process step may well involve some application of herbicide to minimize competition 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 differ considerably in how much input is required - from natural regeneration, through direct seeding to the individual planting of seedlings or whips.

4 **Maintenance:** this is the range of processes required to protect the crop while it grows. 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, which significantly cuts down sunlight penetration to the ground and naturally supresses growth of competitor plants, further interventions are seldom required, except in the case of pest or pathogen attack.

5 **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, usually selectively removing the least good examples. This is a much more labour-intensive process, for less extracted material, than a final clear fell. 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. This step includes extraction of thinnings to the roadside.

6 **Harvesting**: typically, this is a clear fell harvest, and includes forwarding, extraction to roadside. In some forests, continuous cover forestry is practiced as an alternative to clear felling; here only small groups of trees or single stems are removed and the resulting space regenerated. 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 that protect the soil.

7 **Storage and pre-processing (within forest)**: 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.

8 **End of life/reversion**: this will include any processes required to prepare the site for another crop. In the case of a forestry crop, irrespective of is 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. Consequently, this step almost always means preparation for the next rotation of trees.

As discussed earlier, most broadleaved woodland is privately owned with 63% of the privately-owned woodland located in England and 24% in Scotland (Table 3-1). Much of this woodland is not owned for a commercial objective and tends to be left to its own devices with very little active management intervention. Where broadleaved woodland is being managed, some is managed on a clearfell and replant system following the supply chain steps outlined above. On the other hand, a proportion is managed as continuous cover woodland, where only small areas are harvested (sometimes just a single tree) and restocked using natural regeneration; continuous cover forestry is more often practised in privately owned broadleaved woodland than in conifer woodland.

Increased ownership of woodlands by private individuals has contributed to relatively low levels of active management of privately-owned woodlands. The tendency in recent years for companies to buy large areas of woodland, especially broadleaf woodland, and divide it up into small lots to sell to individual private owners primarily for recreational, amenity and lifestyle purposes, has also led to fragmentation of ownership and management strategy, leading to a reduction in active management.

3.3 Costs of production

There are a great many factors that influence the cost of production. In particular, the scale of the operation will have a profound impact on many of the costs per hectare or per cubic metre of product. Other influences include geographical characteristics, such as: the nature of the terrain (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*, or the necessity for repeated herbicide applications; and operational factors such as whether it is new planting or a restocking, choice of ground preparation technique, planting material used, extent of beating up (replacement of failed individual seedlings etc.) required, and planting density. All these factors mean that each of the individual process steps described above may vary significantly from one site to another. Consequently, the expert professional judgment of a practitioner with many years of practical experience performing work studies and producing output guides for the Forestry Commission was drawn upon to define a set of three “typical” scenarios for conventional long rotation forestry:

- Long rotation forestry (LRF) conifers in the lowlands
- LRF conifers in the uplands
- LRF broadleaves

For each of these scenarios, judgments were made of the most likely requirements and characteristics of each process step and costed up accordingly. Each of the three conventional (long rotation) forestry scenarios is described below, and the “typical” costings shown in Table 3-2. In addition, for each of the process steps, low and high costs were estimated to cover situations which were either more favourable than usual or more challenging. This allowed an estimation of the likely range of costs. It must be noted, however, that these do not represent absolute minimum or maximum costs, just the approximate likely range. These low, medium and high costs are given in detail in Table 3-3 to Table 3-5 and a comparison is shown for the establishment phase in Figure 3-3.

The calculated typical costs are consistent with both the standard costs used to estimate eligible costs in woodland grant scheme applications and establishment costs in Wales estimated independently for a recent contract (Saraev, Unpublished data).

LRF conifers in the lowlands scenario. The typical case is medium to large scale productive conifer 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 UKFS (Forestry Commission, 2017) compliance including Section 6.1 Guideline 10 for a minimum of 10% open space, 10% other species and 5% native broadleaves.

LRF conifers in the uplands scenario. The typical case description is as for LRF conifers in the lowlands scenario, though applied to an upland site. However, the assumptions behind the costing for individual process steps will be 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 heavy vegetation.

LRF broadleaves scenario. Broadleaved longer rotation forests are rarely grown in UK primarily for maximum timber production. Although most broadleaved woodlands are created at wide spacing and maintained for amenity and biodiversity purposes, a small proportion may be established at higher density and managed more intensively for quality broadleaves on better sites. This latter system has been used for the LRF broadleaves scenario and has been designed to mirror as far as possible the LFR conifer approach, which is to minimise establishment costs whilst promoting volume production and higher value timber (log) content where site and thinning returns permit. Whilst this is not standard forestry practice in UK, it is more consistent with the concept of growing broadleaves for dual fuel feedstock and timber value.

Silver birch - and downy birch in cooler, wetter locations - has been used as the primary species in this scenario. Amongst its advantages, birch is fast growing, tolerant of a range of site conditions, has high timber density and strength and is planted at 2,500 – 3,000 stems per ha, which equates to comparable planting costs with conifers planted at 2,700 stems per ha. Alternative species could be suited, including sycamore, beech and oak at 4,000, 6,600 and 6,600 stems per ha respectively. These planting densities are significantly higher than those currently used for the majority of broadleaf planting in the UK for which maximum timber production is not the primary aim.

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). 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 broadleaves scenario assumes compliance with UK Forestry Standard (Forestry Commission, 2017) including Section 6.1 (Biodiversity) Guideline 10 which proposes a minimum of 10% open space, 10% other species and 5% native broadleaves.

Table 3-2: Typical costs for LRF establishment and harvesting (£2019)

	Unit	LRF Conifer Lowland	LRF Conifer Upland	LRF Broadleaves
Establishment				
Deer fencing		£255		£710
Draining	£/ha	£40	£75	£40
Cultivation	£/ha	£220	£390	£150
Total ground preparation	£/ha	***£515***	***£465***	***£900***
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***
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 planting	£/ha	***£720***	***£635***	***£585***
Total establishment	***£/ha***	***£2,425***	***£2,100***	***£2,875***
Harvesting				
Thinning	£/m³ end product	£17	£17	£17
Clearfell	£/m³ end product	£9	£10	£12
Residue removal	£/m³ end product	£10	£9	-
Comminution (chipping)	£/m³ end product	£14	£14	£14

Source: Forest Research

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

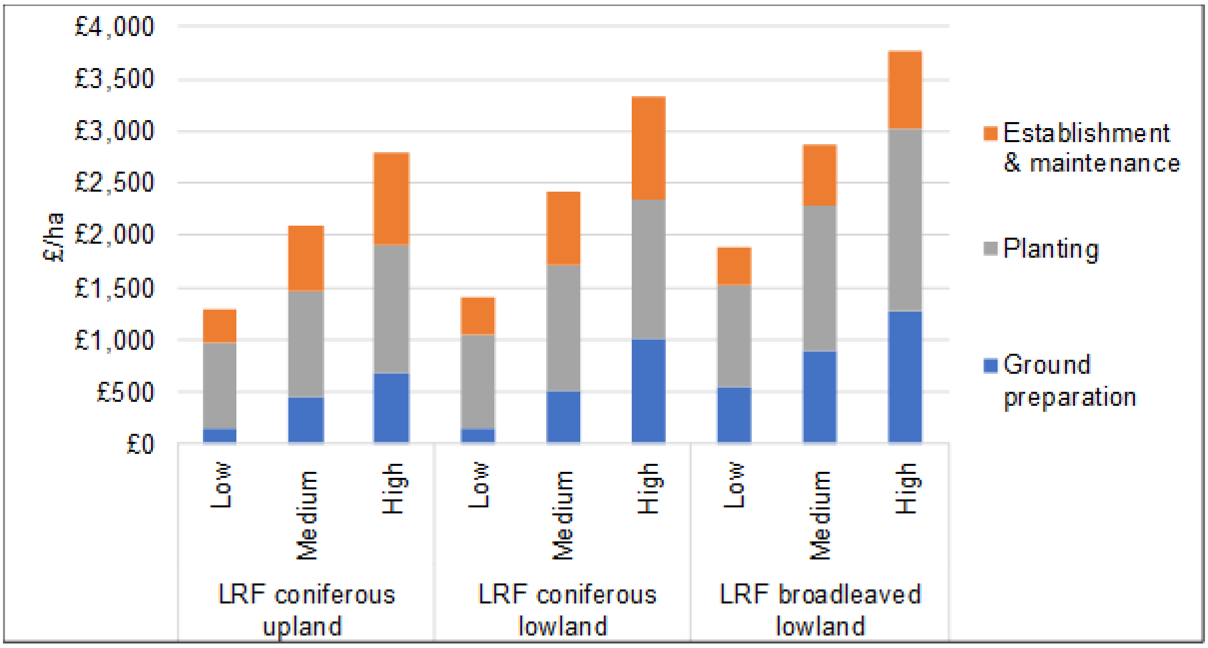


Table 3-3 Range of production costs for LRF conifer upland

Process Step	Unit	Low	Medium	High	Assumptions
Ground preparation and planting					
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 100m / ha; High 200m / 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	£/ha	155	200	350	Lower Y1 10%; Medium Y1 15%; Higher Y1 and 2 15% and10%.
Establishment and 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 3-4: Range of production costs for LRF conifer lowland

Process Step	Unit	Low	Medium	High	Assumptions
					Ground preparation and planting
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 50m / ha; High 100m / 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	£/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 2 20% and 10%.
					Establishment and 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.
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.

Process Step	Unit	Low	Medium	High	Assumptions
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	8	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 3-5: Range of production costs for LRF broadleaf

Process Step	Unit	Low	Medium	High	Assumptions
			Ground preparation and planting		
Deer Fencing	£/ha	460	710	955	20 ha coupes. Increased provision over Conifer 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	£/ha				
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	£/ha	190	345	425	Labour and plants. Increased allowance for cell plant carry-out.
			Establishment and maintenance		
Herbicide	£/ha				Nil for broadleaves.
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.

Converting the costs in the Tables above 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. Consequently, 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 GWh 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.

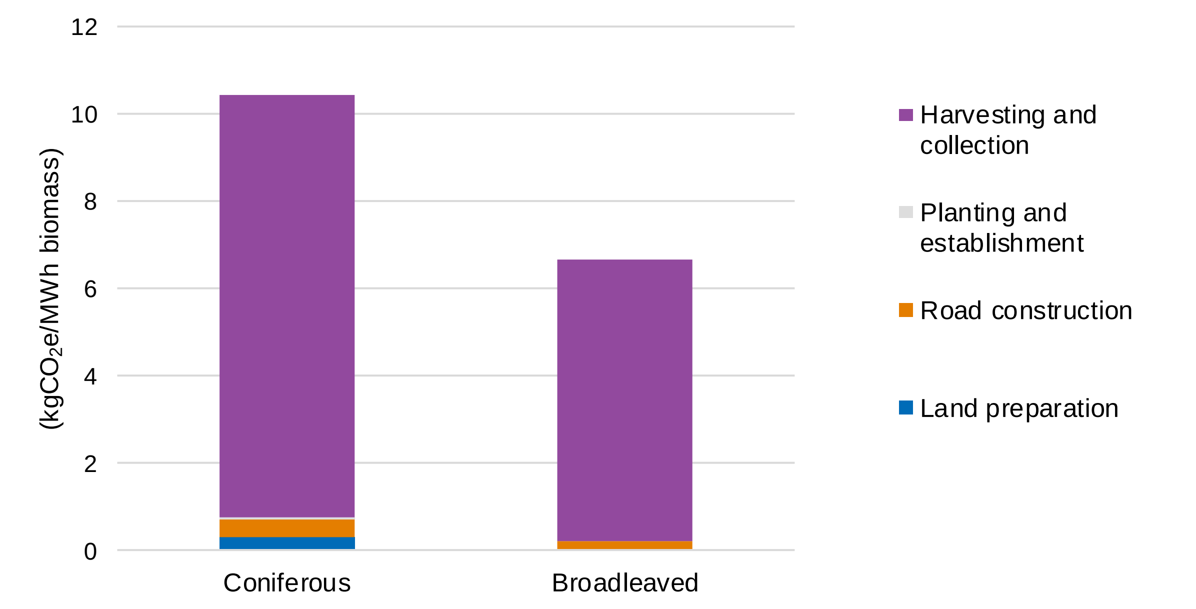
3.4 GHG emissions from production

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.

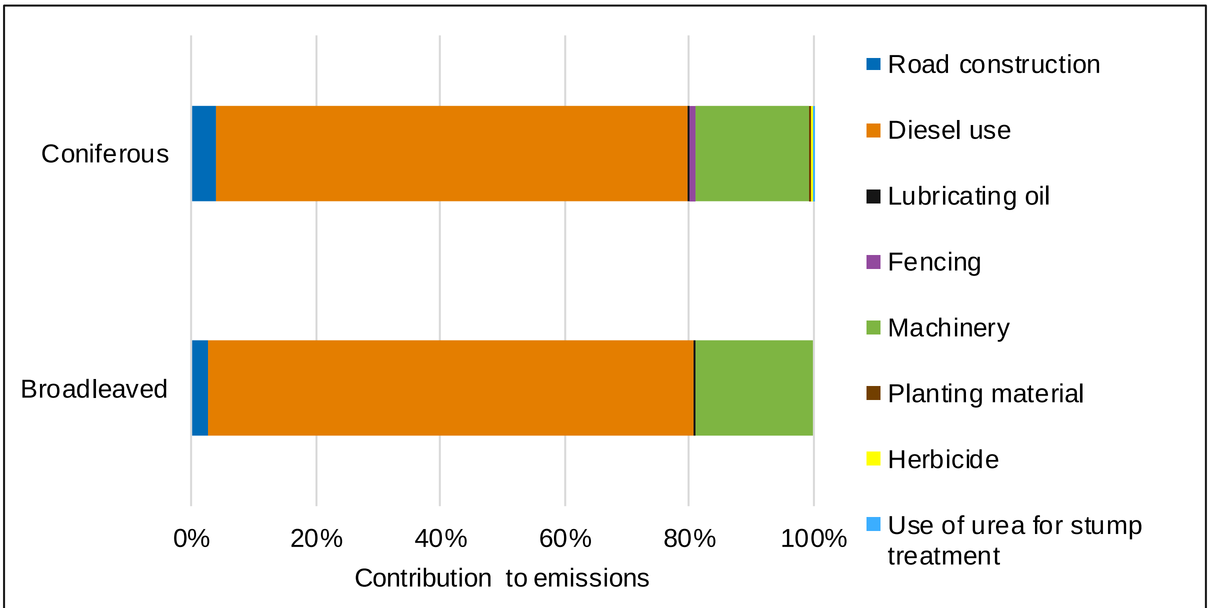
These are shown for coniferous and broadleaved forests in Figure 3-4, and as for energy crops are derived from data in (North Energy, Forest Research and NNFCC, 2018). They reflect the original assumptions in that report, i.e. that wood from coniferous forests comes from forests planted commercially (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 3-5). The other significant source is the production of machinery used for forestry operations.

Figure 3-4: 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 3-5: 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

3.5 Other environmental impacts and benefits

It is generally accepted that trees and forests provide environmental and social benefit. Recent reviews by Brockerhoff (Brockerhoff, et al., 2017) and Aznar-Sánchez (Aznar-Sánchez, et al., 2018) conclude that forests are widely acknowledged as being principle ecosystem service providers. Some national classifications consider up to 100 different forest services but the principal services of relevance to the UK are timber and fuel production; carbon sequestration; flood mitigation, resistance to wind storms, water conservation and regulation; biodiversity protection; nutrient retention; and cultural, spiritual and traditional values and to a lesser extent habitat provisioning services, pollination, seed dispersal, fire regulation and mitigation. However, implicit in this is the assumption of ‘right tree in the right place’ – a common mantra, and that the appropriate management is in place. If either of these elements is wrong, there can be negative impacts. To prevent negative impacts, there is strong regulation and guidance in the form of the UK Forestry Standard which applies to all woodland, regardless of who owns or manages it (Forestry Commission, 2017). The Standard ensures that international agreements and conventions on issues such as sustainable forest management, climate change, biodiversity and the protection of water resources are applied in the UK. The Standard and its supporting series of Guidelines cover key elements of sustainable forest management: biodiversity; climate change; historic environment; landscape; people; soil; and water.

At a national level the study by Eftec, ‘Applying values in ecosystems accounting’ (Eftec, 2015) provides the most comprehensive assessment available of the physical ecosystem service flows which arise from British woodlands and the estimated monetary value of biomass for timber, carbon sequestration, water flow regulation and recreation. The starting point for the estimates is the physical ecosystem stock shown in Table 3-6 . This gives the estimated total extent of woodland, the extent of species type (broadleaved and coniferous) and the volume of timber (by species type and age). It also shows the biomass stock (oven dry biomass), the carbon stock and extent of woodland designated as a Site of Special Scientific Interest (SSSI), as well as the area of woodland in flood risk zones in England and Wales. It shows that most of the standing volume is in conifers and relatively young trees, i.e. in the 41-60 age range. The ability to contribute to flood mitigation is limited due to the relatively small area of woodland in areas with the highest risk (>1% annual chance of river flooding).

Table 3-6: Estimated physical ecosystem stock account for woodlands Great Britain in 2012

		Unit	Coverage	Closing Stock (2012)
Total area[1]		Mha	GB	2.78
Species type[2,3]	Broad leaf	Mha	GB	1.27
	Coniferous			1.51
	Broad leaf	Mm^3	GB	239
	Coniferous	Mm^3		375
Age (years)[4]	0-40	Mm^3	GB	163
	41-60	Mm^3		251
	61-80	Mm^3		105
	>80	Mm^3		109
Biomass stock	Total[5]	Modt	GB	426
Carbon stock	Total biomass[6]	Mt CO_2	GB	780
	Total soil[7]	Mt CO_2	SW England	133
Woodland in flood risk areas[10]	FZ1	Mha[8]	England and Wales	2.61
	FZ2	Mha[8]	England and Wales	0.094
	FZ3	Mha[8]	England and Wales	0.075
Woodland SSSI		Mha[9]	GB	0.243

Source: (Eftec, 2015)

Table 3-7 presents the estimated physical ecosystem service flows for woodland in Great Britain (GB). It shows aggregate GB data on timber harvesting for GB of 0.59 million m^3 of timber for broadleaved woodland and 11.78 million m³ for coniferous woodland, as well as the estimated flow over 20 years of 11.74 million m³ of timber for broadleaved and 235.60 million m³ for coniferous. The annual carbon sequestration was estimated as 6.01 Mt CO_2 for broadleaved and 6.55 Mt CO_2 for coniferous woodland which have been estimated and mapped using FC published rates of carbon sequestration. Thus, conifer woodlands dominate the biomass flows whereas broadleaved woodlands dominate carbon storage. It also accounts for estimated recreational visits (481 million) across GB woodland based on (Sen, et al., 2014) but it was not possible to estimate volumes of water controlled by woodlands in GB.

The estimated monetary account for woodland (Table 3-8) shows the estimated recreational value of GB woodland to be in the order of £1.7 billion a year, carbon sequestration by broadleaved trees of £341million a year and coniferous trees of £372 million a year as well as biomass for timber of broadleaved trees being valued at £9 million a year and coniferous trees at £165 million. This indicates that the recreational opportunities provided by UK woodlands to the wider public at present seem to have a greater value than biomass supply or carbon storage.

Table 3-7: Estimated physical ecosystem service flows for woodland in Great Britain

		Type of ecosystem			
		Woodland			
		Flow (Annual, 2010)		Expected future Flows ('20' years)	
Provisioning	Biomass for Timber	Broadleaved BL	Coniferous C	Broadleaved BL	Coniferous C
		-	-	-	-
	FC Estimates	*0.587million m³ (overbark)*	*11.78 million m³ (overbark)*	*11.74 million m³ (20 yrs; 2012-2031)*	*235.60 million m³ (2012-2031)*
Regulating	Carbon Sequestration	*6.01 $MtCO_2$*	*6.55 $MtCO_2$*	*120.20 $MtCO_2$*	*131.00 $MtCO_2$ (2012-2031)*
	FC Estimates[1]	*10.3 $MtCO_2$ (2010)*		-	
	Water flow regulation	*Difficult to measure in physical terms*		*Difficult to measure in physical terms*	
Cultural	Recreation	*481 million visitors*		*9,620 million visitors (2010-2029)*	

Source: (Eftec, 2015)

Table 3-8: Estimated monetary account for woodland in Great Britain (Eftec, 2015)

		Type of ecosystem service					
		Biomass for Timber		Carbon		Recreation	Water Regulation
		Broadleaved	Coniferous	Broadleaved	Coniferous		
Value	Flow (Annual)	9	165	341	372	1,669 (2010)	Not modelled
	Stock (PV of future flows over 20 years)	127	2,431	5,738	6,254	24,552	Not modelled

Source: (Eftec, 2015)

At a more local level the extent of the ecosystem services can be influenced by the choice of species, the growth rate, the management and in the case of new woodlands the placement within the landscape. Assuming that the species is in general suited to the site, the benefits accruing from new woodland can be greatly enhanced by careful location. Examples include:

- In flood plains to attenuate flood peaks and sift out debris thereby reducing downstream flooding as shown in the case study ‘Slowing the Flow at Pickering’ in (Thomas & Nisbet, 2016).
- In riparian areas to increase infiltration rates so that any overland flow from upslope fields moves down the soil profile within the woodland thereby reducing particulate and dissolved nutrients moving further downslope and polluting the river systems as shown in the case study PontBren in (Thomas & Nisbet, 2006).
- On slopes to reduce soil erosion as shown in the case study ‘Rest and be Thankful’ in (Rayner & Nicoll, 2012).
- As shelter belts for crops or animals (Gardiner, et al., 2006).
- To link existing woodlands and hedgerows thereby providing habitat networks.
- To provide health and wellbeing opportunities.

3.6 Current challenges and barriers to production

A range of challenges and barriers to production have been identified from the stakeholder consultation and experience of the project team.

3.6.1 Technical

Several stakeholders commented that there were no fundamental technical barriers, though there were still technical challenges to overcome (the overall deciding factors were financial, which are covered in the next section). Several contributory issues were mentioned, and these can be grouped into the following specific areas of concern.

- Access
  - Access to woodlands for harvesters and timber extraction can be difficult especially for large machinery, such as harvesters. Activities on some sites can be hampered by the need to protect the soil, requiring low ground pressure machinery.
  - Poor access to highways can make it very difficult to mobilise harvested material and take it to market.
  - Infrastructure can be required at the central depot for the storage of harvested material and/or equipment. Hard standing may be required to allow harvested roundwood to be stacked for air drying, or for wood chipped on site to be stored and dried.
- Feedstock properties
  - Ash content. Ash is the non-combustible mineral content and is higher in bark and foliage than in wood. It produces a residue in the combustion equipment and can cause slagging and fouling. Material with a high bark to wood ratio - for example branches, small diameter stems such as generated from early thinnings and coppice, and brash - are high in ash and less attractive to feedstock purchasers. Contamination with soil also adds to ash content. Pelleting plants generally require a relatively low ash content.
  - Moisture content. Freshly harvested wood has a high moisture content, typically 50% or more. This water is heavy for transporting and unsuitable for combustion, so biomass feedstocks need to be dried before use, unless the system is specifically designed to use high moist content biomass. Moisture content can be achieved passively, by air drying,

which takes time, or actively, with a dryer, which is quicker but much more expensive, both financially and in terms of carbon emissions.

 - Potentially desirable chemical compounds. As an alternative to more conventional, combustion-based conversion, wood can be used for advanced processes or for conversion to more valuable products. Such technologies can include conversion of cellulose into sugars and fermentation of these and intrinsic sugars to bioethanol, or exploitation of volatiles and other chemicals in a biorefinery for the production of fine chemicals. High levels of sugars or other specific compounds can help increase the value of wood products.

- Availability of infrastructure and resources
  - Specialised machinery. Efficient forest management, particularly harvesting and thinning, requires specialised, sophisticated machinery which can be extremely expensive. High usage levels are required to justify this expense, which means it is generally owned by large contractor companies. This means a limited number within the country. It also means that if new, innovative products are to be brought in from other countries there has to be sufficient, established demand. This is further exacerbated if modifications are required for UK conditions.
  - Labour force. In the UK, as well as many other countries, there is a shortage of trained foresters and insufficient numbers of young people opting for training. If there were to be a demand for a significantly increased level of planting and activity it is likely that the availability of labour could be a limiting factor. Also, with an ageing workforce, the enthusiasm for adopting novel practices and sophisticated, computer-based equipment can be lower than with a younger workforce.
  - Planting material. If there were to be a significant increase in planting activity there could be a delay in the production of a sufficient quantity of suitable planting material. This constraint could be exacerbated if a wider range of suitable species, provenances or genetically improved material is recommended.
- Logistics
  - Bioenergy feedstocks have a low energy density, especially if they have not been dried. They are therefore bulky and expensive both to transport and to store.
  - Many biomass feedstock processing facilities require a large-scale operation for efficient, cost effective operation. For a conventional pelleting plant this might be of the order of tens of thousands of tonnes per annum, however for a gasification and Fischer-Tropsh plant it could be of the order of millions of tonnes per annum. The challenge of sourcing sufficient feedstock, bringing it to a single location, and storing it for use is very significant.
- Properties of high yielding, exotic species
  - Frost tolerance. Potentially high yielding, exotic tree species such as some Eucalyptus varieties, are likely to be sourced from countries with warmer climates, and consequently may have lower tolerance to frost and periods of cold weather than native species, potentially leading to significant losses from the crop in cases of a cold snap.
  - Water demand. Some exotic species may have high water demands, which can lead to local environmental impacts and potentially competition with other nearby crops.

3.6.2 Economic

Many comments were received from stakeholders concerning the economics of forestry, biomass production and the grant system.

Comments received from a number of stakeholders were that the grants system is complex, fragmented and restrictive in what can be done, and species planted. It was suggested that a single environmental scheme that allowed multiple benefits to be considered together (carbon sequestration, biodiversity, flood control, as well as timber/bioenergy production) would be helpful. Specific comments on grant schemes were:

- Cost of operations compared to the value of products. Although there are few fundamental technical problems that cannot be addressed, the difficulty is whether the value of the products justifies the cost involved. In the case of conventional (long rotation) forestry it is the value of the sawlogs and associated longer lived timber products that drives (and funds) production. Investing in innovative technologies or activities can only be justified when the value of the products is sufficient to make it worthwhile. This can be challenging where the only product being removed is wood which will go to bioenergy and no higher value products are being removed, e.g. at the thinnings stage. A higher price for bioenergy feedstocks would encourage more investment.
- Cash flow. The timescales associated with conventional forestry are very long. The bulk of the investment is required at the outset, with limited returns until the final harvest perhaps 40 years later in the case of a conifer crop, or up to 100 years or more for a broadleaf crop such as oak or beech. Short rotation forestry potentially reduces this timescale to 15-20 years, but this still ties up funds for a considerable period. Early thinnings currently bring minimal returns. Experience in other countries, for example Austria (DTI Global Watch mission reports Energy from biomass – a mission to Austria and Denmark 2003) and the USA (From tree to fuel: woodfuel supply chain infrastructure in the USA, 2005), indicated that woodlands were better managed (i.e. there is more regular trimming and thinning) when there was a bioenergy market for small dimension material, particularly early thinnings. It was suggested that interim maintenance payments, perhaps based on carbon sequestered, could be a way of ameliorating cash flow concerns.
- Grants only cover a proportion of the initial costs. Although grants exist to help with establishment and maintenance costs and the provision of infrastructure, they typically do not fully cover these costs, so additional funding must be sought to cover the difference. Specific grants come and go, increasing the difficulty in long term planning. Specific grants to achieve desirable ends such increased access to woodlands (such as the Woodfuel Woodland Improvement Grant) can be effective. The emphasis on broadleaf planting, despite a lack of demand for broadleaf timber, can detract from the concept of a forest as a cost effective, productive resource.
- Land costs. The rise in land costs make the acquisition of new land for expansion and afforestation very expensive. This means that any land purchased must be made to be as economically profitable as possible, and tends to allow afforestation on relatively marginal land with low productivity.
- Several stakeholders have found the paperwork associated with grant applications, and the timescales before they are awarded, off-putting. They also commented that they can be restrictive in terms of the species that can be planted.
- Market uncertainty. Potential changes in market demand over the long timescales associated with forestry increase uncertainty, which increases the risks associated with investment, potentially increasing the cost of capital.
- Scale of operation. Economies of scale mean that larger operations can often be more profitable, reducing overheads and assisting investment. It also allows a rolling programme of forest management so that each year sees both planting and harvesting, thus helping to smooth out cashflow. However, this also requires higher investment and greater financial exposure. The scale of the market for all forest products, including bioenergy feedstock, will

have an impact on attitudes and market confidence, and engendering confidence in a long term bioenergy market may therefore be important in allowing the market to develop to a size where economics of scale can be realised.

- With an industry such as forestry in which a variety of co-products can be produced in parallel, there must always be sufficient market for all products if there isn't to be a glut of one, thus potentially causing a price fall. The age structure of a forest, and the choice of thinning ages can help to ensure a balance of sawlogs, small roundwood and bioenergy feedstocks on the market.

3.6.3 Social/cultural

The main points raised stakeholders were the need for impartial, definitive information, significant levels of engagement and knowledge sharing, and the perceived lack of leadership and co-ordination from Government. Information and experience sharing are required on topics such as different species, different management systems and equipment, and integrated land management incorporating an element of forestry. These points need to be addressed to minimize the repetition of mistakes and consequent losses. More (and better) communication on the best use of forest biomass from a financial and GHG point of view, and appropriate processing and distribution is needed.

- Attitudes
  - Attitudes of landowners. Informing and engaging landowners is vital. One stakeholder from a representative body commented that there is a need to educate farmers to plant more woodland. Biomass can potentially offer another income stream from small dimension material such as early thinnings and brash.
  - Attitudes of the general public. The general public can often be poorly informed about the role of forestry management operations and can frequently be opposed to felling. It was commented that the opportunity to challenge the grant felling licences introduced in the Republic of Ireland can make the grant of the licences a much more time-consuming and potentially expensive process. Significant information and education in the role of active woodland management in the promotion of biodiversity, and of felling as a necessary activity for the production of a sustainable, low carbon product, would be very valuable.
- Tying up land
  - Long term commitment. Forestry requires a commitment of land for decades, with uncertain, variable markets. The land will be unavailable for other activities, even if these become highly attractive. In many cases, once turned over to forestry the grant of a felling licence will require the land to be subsequently re-planted, effectively tying up the land in perpetuity.
  - Unfamiliar business model. It was commented that there is a strong cultural resistance to turning land over for forestry even where the economics can be seen to stack up. In lowland regions, land owners are willing to plant but the case needs to be linked to wider environmental benefits. For landowners familiar with other crops, the move into forestry involves an unfamiliar business model with much longer timescales, unfamiliar activities and the requirement to work with a new range of contractors and equipment. Those who adopted SRC felt that the promised market was never delivered.
- Uncertain markets
  - A landowner needs to be confident that at the time of harvest, potentially decades in the future, the market will be strong for all wood products produced.

- Land ownership
  - A wider range of ownership. Partially as a result of turbulence in conventional financial markets, demand for woodland for investment purposes has grown significantly over the past 20 years or so. For many of these new owners, production forestry is not an aim, with the land value itself, recreation, amenity, lifestyle, wildlife and biodiversity aims all involved. Many would object to harvesting, and in some cases even to many kinds of active management.
  - Fragmentation of ownership. Large areas of woodland are frequently bought up and sold on in small lots for lifestyle, investment and amenity reasons. This fragmentation brings a much wider section of the general public into contact with the countryside but can make coherent management and harvesting almost impossible. This can usually only be done cost effectively if a number of such owners agree to operate together, however this requires a commonality of purpose that can often be lacking.

3.6.4 . Summary of challenges

An overview of the challenges discussed above is given in Table 3-9, which shows that many of the barriers identified by stakeholders are non-technical in nature.

Table 3-9 Overview of challenges in increasing production from LRF

Overall challenge	Specific requirement/issue	Discussion
Costs	Cost of operations compared to the value of products	Most technical issues can be addressed; the issue is whether it can be done at a cost that is justified by the value of products produced. This can make investing in innovations unattractive. The ratio of cost to returns lies behind many challenges.
	Cash flow	Conventional forestry is a very long term undertaking, potentially running over generations. Most investment is required at the outset, with little or no return for years or decades. SRF reduces this timescale, but it is still likely to be 10-20 years before income is realized.
	Grants cover a proportion of set-up costs	Although grants can help with up-front establishment costs, they cover a proportion, not the entire expense, meaning that additional funding must be found to make up the shortfall. This also applies to grants for the laying of infrastructure such as in-forest rides and access roads.
	Land costs	Land costs are very high making the acquisition of new land for expansion very expensive and meaning that it must be made to be as economically productive as possible.
	Bureaucracy, timescales and constraints of grant programmes	The paperwork and timescales associated with obtaining grant support was viewed as off-putting by some stakeholders. The constraints imposed by grant conditions, for instance with respect to which species may be planted, were viewed as potentially restrictive.
	Uncertainty of market for end products, time scales involved and market fluctuations	Uncertainty in business increases costs and reluctance to invest.
	Scale of operation	Optimum economics are achieved with economies of scale. However, this requires concomitantly large investment and financial exposure.
Access	Access for harvesters, large equipment	Many woodland sites do not have well established access for large machinery such as harvesters. Low ground pressure machinery can be required to avoid damage to soil structure. Access from remote woodland sites to national distribution communications, such as main roads, ports or railways, can be poor.
Feedstock properties	Physical infrastructure, such as hard standing	Sites require areas of hard standing to allow harvested wood to be stacked prior to transport, in particular to allow air drying of roundwood and possibly storage of woodchips.

Overall challenge	Specific requirement/issue	Discussion
Feedstock properties	Ash content	Bark and foliage have high ash content. Smaller diameter material, such as branches, early thinnings and coppice stems, and low value material such as brash, have a high proportion of bark and high ash content. High ash content feedstock is not suitable for most current combustion equipment, nor for most pellet mills.
	Moisture content	High moisture content feedstock requires drying before it can be used. This is either time consuming (passive drying) or expensive (active drying). Until it is dry, feedstock is much heavier, thus more expensive to transport.
	Potentially desirable compounds such as fermentable sugars, or volatiles for biorefinery activities	One model to achieve higher returns from forest products is the manufacture of higher value co-products, such as ligno-cellulosic bioethanol, or even fine chemicals from biorefining.
Availability of infra-structure/ resources	Availability of specialized, sophisticated, expensive machinery	To achieve efficient operations, especially harvesting, highly sophisticated and expensive machinery is required. In order to achieve high usage levels to justify the expense, these tend to be owned by large contractor companies, meaning availability within the country is limited. There has to be a well proven requirement, of sufficient scale, for these companies to invest in new, specialist, innovative machinery that may be available in other countries. Even then they may require modification or adaptation to UK conditions.
	Availability of trained labour force and contractors	Many countries are reporting a shortage of trained foresters and uptake of training opportunities, especially with younger people. Much of the existing workforce is therefore older which can lead to reluctance to fully exploit the capabilities of sophisticated, computer based, new technologies. In addition, if a significant increase in planting were to be required, the workforce available to meet the demand might not be available immediately.
	Availability of efficient feedstock drying equipment	Active drying of biomass feedstock, especially woodchips, reduces the time to achieve suitable moisture content, however, increases the costs (and potentially GHG emissions). Much active drying equipment is not as efficient as it could be.
	Availability of planting material	If a significant increase in planting were to be demanded, there could be a lag before sufficient, suitable planting material were to be available.

Overall challenge	Specific requirement/issue	Discussion
Logistics	Bulky material expensive to transport and store	Bioenergy feedstocks are of low energy density, especially if they have not been dried. This makes transport expensive and requires large storage facilities.
	Scale	Most efficient, cost effective feedstock processing requires a suitable scale of operation. For a pelleting plant this is likely to be of the order of tens of thousands of tonnes per annum. For a gasification plant or a biorefinery it may be of the order of millions of tonnes per annum. The logistics required to source, bring this quantity of feedstock to the plant and store it can be very challenging.
Properties of high yielding species	Frost tolerance	Novel tree species can give very high yields, however they are likely to be non-native, usually from more southerly countries. They can have reduced frost tolerance compared to native species, potentially leading to significant mortality.
	Water demand	Some potentially high yielding species can have high demand for water, which can cause difficulties for landowners, ground structure and other users of sub-surface water.
Attitudes	Attitudes of landowners	Landowners can be conservative in attitude and reluctant to experiment with unfamiliar crops, business models or innovations. A new generation of owners of woodlands for investment, wildlife or recreational purposes are not necessarily well informed about woodland management and can have non-interventionist attitudes, especially to harvesting.
	Attitudes of general public	The general public can be misinformed and may have objections to felling woodland. There can be a tendency to challenge the grant of felling licences which can cause delays and additional costs.
Tying up land	Long term commitment; May well not be allowed to revert	Forestry requires a long term commitment. It means the land will be unavailable for many other activities, potentially indefinitely. Grant of a felling licence almost always requires subsequent replanting, so even an SRF crop may be viewed as tying up the land in perpetuity.
	New crop; new business model	For landowners who do not currently have significant forestry activities, a change to forestry can involve a significant change in business model, unfamiliar activities and engagement with a new set of contractors.
	Tax position for succession	As a result of the long term nature of forestry (in common with agriculture) the issue of succession is likely to be significant, with a forest passing through generations. The inheritance tax position for forestry can be complex, and protection of new plantings is no longer in place.
	Uncertain markets	Owing to the long term nature of forestry, the crop owner needs to be confident, not in the current market for the products he/she will produce, but the market at the time of harvest, which could be years or decades in the future.

Overall challenge	Specific requirement/issue	Discussion
Land ownership	Range of ownership aims other than production forestry	There have been many newcomers to ownership of woodland in the last twenty years or so, predominantly for investment purposes in the context of uncertain financial markets. Ancillary reasons include amenity and recreation value and wildlife and biodiversity aims. Production forestry can be a low priority, and owners can have views that harvesting, and even management, are to be avoided.
	Fragmentation	Companies have been set up that purchase large blocks of forest and re-sell then in much smaller blocks. This helps to widen woodland ownership and helps to bring the general public into greater contact with the countryside, however the scale of such plots can make management or harvesting uneconomic unless many such owners agree to operate together.

4 Short rotation forestry

4.1 Introduction

Short rotation forestry (SRF) offers many of the benefits of forestry grown on a more conventional rotation, but with a number of potential advantages. The benefits to ground water control, especially in riparian sites and flood plains, soil quality and stabilization, biodiversity and air quality obtainable from conventional forestry are all available. However, by planting fast growing species, significant biomass yield can be obtained over a timescale of ten to twenty-five years, rather than the forty to one hundred years for more conventional forestry. This has significant benefits to cash flow for the land manager, and also helps reduce the time delay between the emission of biogenic carbon as a result of combustion and the subsequent uptake of atmospheric CO_2, often referred to as the “carbon debt”.

The shortening of the rotation does reduce 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.

There have been trials of SRF, using a range of different tree species, broadleaf and conifer, indigenous and exotic, established in 2010 to 2013 at a number of sites around the UK. To date, however there has not been extensive uptake of the approach. The greatest interest is concentrated in South West England using a range of eucalypt species, but these crops have not yet reached full rotation so a robust evaluation of the carbon, financial and environmental implications is not available.

4.2 Production

Most of the process steps associated with short rotation forestry are broadly similar to those for conventional LRF (Section 3.2), 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 unlikely to take place (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 conifers 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.

4.3 Costs of production

4.3.1 Costs in each process step

Two typical scenarios have been defined for SRF:

- SRF conifer scenario
- SRF broadleaved scenario

As for LRF (Section 3.3) there are many variables that affect prices, and so in addition to the “typical” costs in each scenario, low and high costings have been estimated. As with LRF, these do not represent minimum and maximum costs, but the likely range. The scenarios are described below and typical costs are summarised in Table 4-1. These low, medium and high costs are given in detail in Table 4-2 and Table 4-3.

SRF conifer scenario: Fast growing conifer 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 broadleaves, however these amendable (increased and reduced) costs are assumed to lie within the overall envelope of costs allowed.

The typical case is medium to large scale productive conifer forestry, predominantly 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 towards the Medium and Higher cost outcomes, but this will not always be the case.

SRF broadleaved scenario: Fast growing native broadleaves 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. The model includes 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 regrowing 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 broadleaves.

Silver birch - and downy birch in cooler, wetter locations - has been used as the primary species in this scenario. Amongst its advantages, birch is fast growing, tolerant of a range of site conditions, has high timber density and strength and is planted at 2,500 – 3,000 stems ha^{-1} which equates to comparable planting costs with conifers planted at 2,700 stems ha^{-1}. Various other species could be suited, including sycamore, beech and oak at 4,000, 6,600 and 6,600 stems ha^{-1}, or sweet chestnut older coppice. The Lower cost outcome uses poplar setts.

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). New planting will tend towards the Lower cost outcome, with restocking towards the Medium and Higher cost outcome.

Table 4-1: Typical costs for SRF establishment and harvesting (£2019)

	Unit	SRF Conifer	SRF Broadleaves
Establishment			
Deer fencing		£255	£640
Rabbit control		-	£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
Establishment and			
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	£585
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 4-2: Range of production costs for SRF conifer

Process Step	Unit	Low	Medium	High	Assumptions
Ground preparation					
Deer Fencing	£/ha		255	570	20 ha coupes. As Conifer Lowland LRF
Rabbit Control	£/ha				Nil expected
Spirals	£/ha				N/a
Draining	£/ha		40	75	As Conifer Lowland LRF
Cultivation	£/ha	150	220	410	As Conifer Lowland LRF, with allowance for greater stocking density in Higher scenario
Planting					
Plant supply	£/ha	595	650	900	As Conifer 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	£/ha	170	340	495	As Conifer Lowland LRF, with allowance for greater stocking density in Higher scenario
Establishment and maintenance					
Top up spray (Hylobius)	£/ha		90	230	As Conifer 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 Conifer Lowland LRF, with allowance for greater stocking density in Higher scenario
Cleaning/ respacing	£/ha		70	105	As Conifer Lowland LRF
General maintenance	£/ha	160	220	275	As Conifer Lowland LRF
Forest-scale operations	£/ha	45	55	80	As Conifer 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	1,00 0	1,250	1,600	Based on mounding and brash matt removal cost assuming 100 t / ha at 5 - 7 tonnes / hr. Very rough estimate, albeit further refinement possible given time.

Table 4-3: Range of production costs for SRF broadleaf

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	£/ha	110	345	675	Medium scenario as Broadleaved LRF, but with greater extremes at Lower and Higher ends.
					Establishment and maintenance
Top up spray (Hylobius)	£/ha				Nil for broadleaves.
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			45	As Broadleaved LRF.
General maintenance	£/ha	160	220	275	As Broadleaved LRF.
Forest-scale operations	£/ha	45	55	80	As Broadleaved LRF.
Land rent	£/ha		131	181	As Conifer SRF.

Process Step	Unit	Low	Medium	High	Assumptions
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 matt removal cost assuming 100 t / ha at 5 - 7 tonnes/hr. Very rough estimate, albeit further refinement possible given time.

4.3.2 Estimation of the cost of production for SRF

The data in Table 4-2 and Table 4-3 have been used in a simple cost model to calculate the overall costs of production. These are shown in Table 4-4 for the low, medium and high cost data sets, using discount rates of 5 and 10%, and assuming a moisture content on harvest for broadleaf of 50% and for conifer of 55%. For the discounted values, production has also been discounted so that the cost is a levelized cost of production and represents what the farmer or land owner would need to receive to achieve an internal rate of return equal to the discount rate. The values in Table 4.4 include chipping but make no allowance for land rent. While costs of production on a per ha basis are higher for broadleaf SRF, the higher yield that is obtained means that costs per odt or GJ are lower. For the medium cost case, the chipped SRF would need to be sold for £9.3/GJ (coniferous) or £6.8/GJ (broadleaf) to allow an internal rate of return of 5% to be achieved.

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 Table 4-5where the medium case assumes the low land rent assumed in the energy crops analysis of £131/ha, and the 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 about 20 % to the cost of the wood chip produced, apart from the low case where no land rent is assumed to be payable.

Figure 4-1 shows the contribution from different costs elements when costs are undiscounted and Figure 4-2 the contribution when the discount rate is 5%. Harvesting costs are the most significant element of production costs, although if land rent is payable (shown as part of the establishment and maintenance costs in the graph) then it also makes a substantial contribution.

Table 4-4: Cost of producing wood chips from SRF (15-year rotation excluding land rent)

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

Table 4-5: Cost of producing wood chips from SRF (15 year rotation including land rent)

Parameter	Plant type	Units	Case	Un-discounted figures	5% discount rate	10% discount rate
Production cost per hectare	Conifer	£2019/ha	Low	7,632	4,167	2,594
			Medium	14,012	8,119	5,352
			High	19,722	11,612	7,801
	Broadleaf		Low	8,560	5,009	3,391
			Medium	14,667	8,678	5,871
			High	20,801	12,541	8,658
Total production	Conifer	odt/ha	Medium	80	37	17
	Broadleaf		Medium	120	55	26
Production costs per odt	Conifer	£2019/odt	Low	95	113	153
			Medium	175	219	315
			High	247	314	459
	Broadleaf		Low	71	91	130
			Medium	122	158	226
			High	173	228	333
Production costs per GJ	Conifer	£2019/GJ	Low	5.0	5.9	8.0
			Medium	9.2	11.5	16.6
			High	13.0	16.5	24.2
	Broadleaf		Low	3.8	4.8	6.9
			Medium	6.4	8.3	11.9
			High	9.1	12.0	17.5

Figure 4-1: Contribution of process steps to levelized cost of SRF production (discount rate of zero)

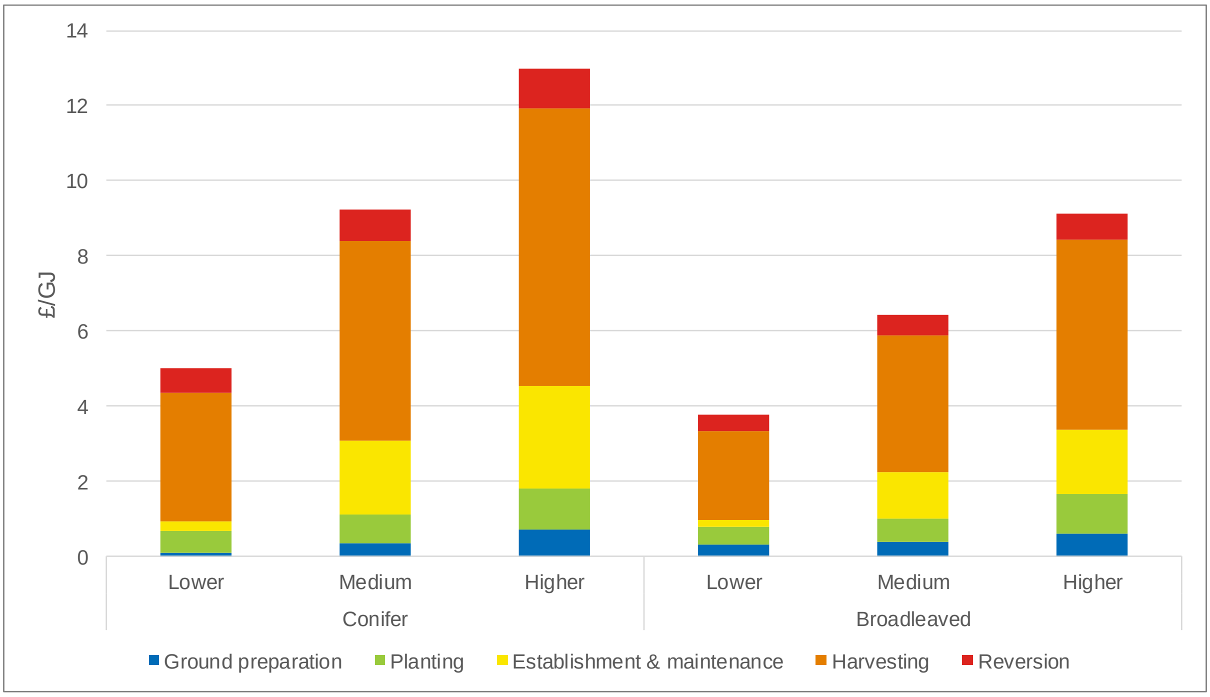
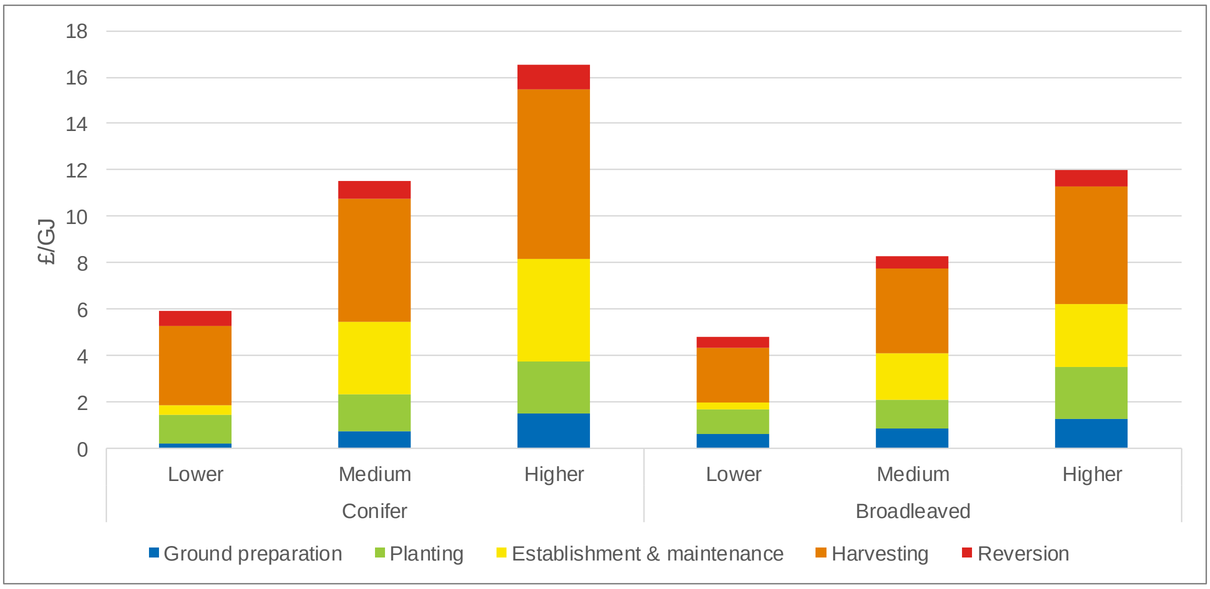


Figure 4-2: Contribution of process steps to levelized cost of SRF production (discount rate of 5%)



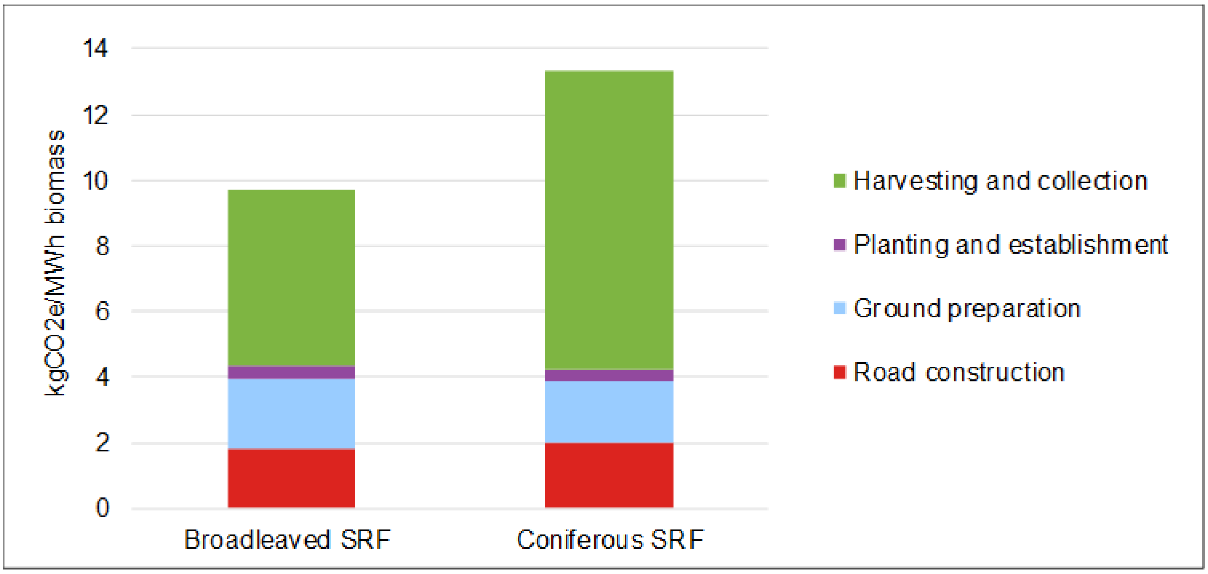
4.4 GHG emissions from production

GHG emissions from 'typical' production of SRF broadleaf and coniferous from ground preparation, through to harvest and collection are shown in

Figure 4-3. They exclude changes in emissions from soil carbon, which are discussed further below, but include emissions from all operations associated with cultivation from planting to harvesting and the emissions associated with 'capital goods' (fencing and machinery) and production of agrochemicals, as well as emissions associated with developing and maintaining access roads within the site. Emissions are estimated to be 9.7 kg CO_2e/MWh of biomass feedstock for SRF broadleaf and 13.3 kg CO_2e/MWh for SRF coniferous. A further breakdown of emissions by source is in Figure 4-4. Sites are assumed to have fencing for protection from pests while establishment takes place, herbicide is applied during planting and establishment phase, and urea application for stump treatment at harvesting. No fertilisers are assumed to be applied.

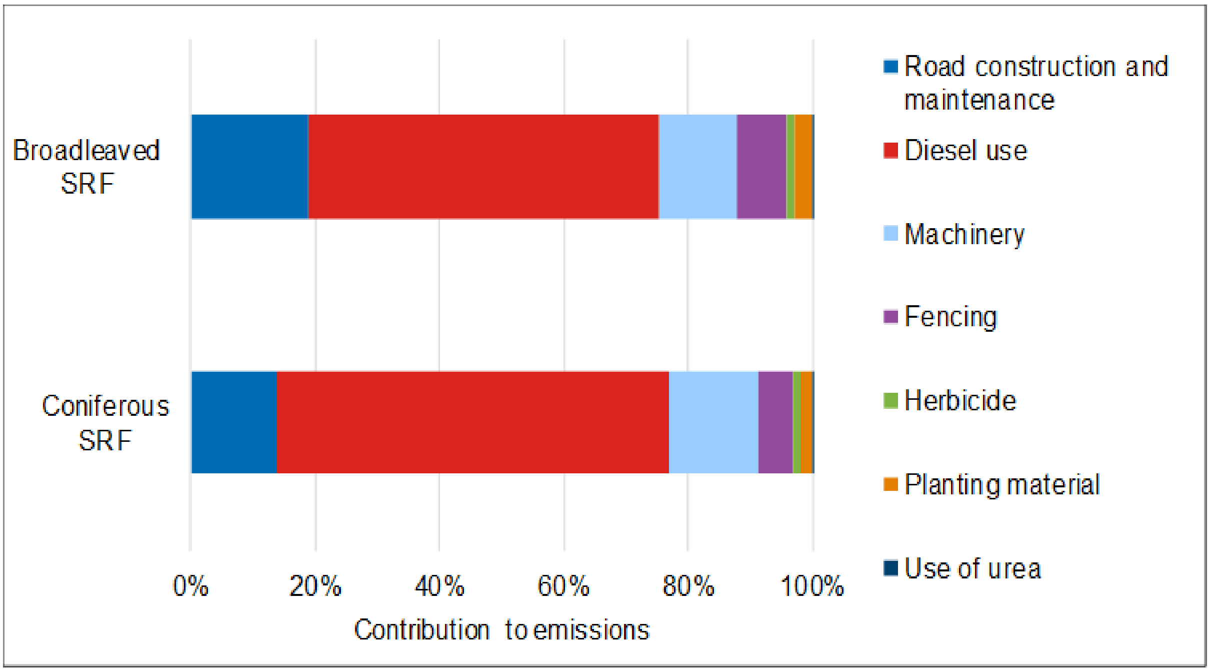
For both SRF broadleaf and SRF coniferous, emissions arise principally in the harvesting and collection step, and arise mainly from diesel use, although emissions associated with road construction and ground preparation are also significant. Diesel use is the dominant source of SRF emissions (Figure 4-4), contributing circa 60% of the overall emissions for both broadleaf and coniferous, with around 80% of the diesel consumption arising in the harvesting and collection step. Road construction accounts for 19% and 14% of emissions for SRF broadleaf and coniferous respectively, if road construction were not required or is excluded from the production estimate then the overall emissions would be reduced to 7.9 kg CO_2e/MWh and 11.5 kg CO_2e/MWh respectively.

Figure 4-3: GHG emissions from production of SRF by process step



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 4-4: Sources of GHG emissions in production of broadleaf 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.

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 4-6, and as for energy crops are based on data from (Richards, et al., 2017). 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 4-6: 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[13].

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

4.5 Other environmental impacts and benefits

Impacts and benefits are predominantly the same as those for conventional forestry as described in Section 3.5.

[13] 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.

4.6 Current challenges and barriers to production

Essentially these are very similar to those described for conventional forestry (Section 3.6). However, the potential expansion from planting historically on “forestry land” into planting on “agricultural land”, is likely to change the types of landowner involved. This will accentuate issues such as an unfamiliar, much longer-term business model, and unfamiliar contractors and equipment. In addition, there are likely to be concerns over the potentially irrevocable conversion of agricultural land into forest land with the attendant feeling of lock-in. SRF is likely to use a wider range of species than LRF and managers, including those who are experienced in LRF, will need better knowledge on how to manage new species.

5 Innovations in forestry

5.1 Innovations applicable to current practice

5.1.1 Overview

This section gives an overview of the innovations identified on the basis of the literature review and expert knowledge within FR. Key innovations are then described in more detail in Sections 5.1.2 to 5.1.15.

5.1.1.1 Planting stock preparation

When a site has been identified as suitable for bioenergy crops in the form of long or short-term forestry, several factors will influence the material to be established and its management.

Species selection will largely be governed by climate, location and economics, as well as social and political objectives. As a result, yield is unlikely to be the only, or even necessarily the primary concern, when choosing species, and this applies particularly to broadleaf woodland, for which recreation, amenity, biodiversity, lifestyle and investment considerations often play a significant part in decisions.

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 seed-stock 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. In the case of Sitka spruce for example, one study (Lee & Watt, 2012) found that most typical full-sibling families will give 20% more sawlogs than seed orchard crops of Sitka spruce, but that the very best full-sibling families, selected mainly for good straightness, could give up to 30% extra. (Jansson, et al., 2017) found that tree breeding can improve volume growth by 10-25%, and that use of such selection gives a better return on investment and a shorter rotation period compared to unimproved forests.

Four specific innovations related to planting stock preparation have been identified and are discussed further below:

- Species selection (Section 5.1.2)
- Provenance selection (Section 5.1.3)
- Genetic selection (Section 5.1.4)
- Species mixture (Section 5.1.5)

5.1.1.2 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 and is discussed further in Section 5.1.6.

5.1.1.3 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 use of light quality and intensity (Hernandez Velasco & Mattsson, 2019), manipulation of the seedling type (Böhlenius & Övergaard, 2016) and improvement in cutting systems.

- Planting/seeding techniques (Section 5.1.7)
- Initial spacing (Section 5.1.8)
- Enrichment planting of understocked woodlands was raised as a potential innovation but has been covered within Section 5.1.2 on species choice and is not discussed further as a separate section.

5.1.1.4 Cultivation and maintenance

Although currently seldom used in UK forestry, fertilizer can help to improve establishment and initial growth rate. Digestate from Anaerobic Digestion 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. Experiments have been performed in the UK and particularly in other European countries on the use of wood ash in forestry, and also on granulating it to minimize the extent to which it blows around after application, and to promote a slow release of minerals. Use of organic fertiliser applications is discussed further in Section 5.1.9.

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 5.1.10.

5.1.1.5 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. There are different thinning strategies involving different aspects of management practice, e.g. age of first thinning, frequency of subsequent thinning, type and intensity. Thinning typically takes place at periodic intervals over the rotation and, as time goes by, the value of the material removed during the thinning increases. 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, which is typically of larger diameter than thinnings from a commercial plantation, however the lack of previous management frequently means that the form of much of the material obtained is too poor for acceptance at a sawmill though suitable for bioenergy end uses.

- Early thinning of whole stems was raised as a potential innovation but has been covered within the section on harvesting technologies and is not discussed further as a separate section.
- Thinning of overstocked woodlands was 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. This has therefore not been discussed further as a separate section.

5.1.1.6 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:

- Adjustments to top diameter (Section 5.1.11)
- Removal of stump to ground (Section 5.1.12)
- Residue harvesting (Section 5.1.13)
- Stump and root removal (Section 5.1.14)
- Harvesting technology (Section 5.1.15)

5.1.2 Species selection

5.1.2.1 Description

The priorities directing species selection in the past will not necessarily be the most important for current and future planting, especially when bioenergy feedstock production, rather than, or alongside, timber production, becomes part of the consideration. This means that a number of species that have been little planted in the past now warrant further investigation.

Commercial LRF has focussed on a relatively narrow range of species chosen primarily for their rapid volume growth and good stem form but implicitly also for their survival. Ease of establishment, seed availability, susceptibility to disease and browsing damage are secondary considerations. However, current thinking includes other considerations such 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 conifer 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 conifer species.

There are no simple rules relating growth to species characteristics or even to genus characteristics because of the differences from one species to another, even within a genus. Characteristics that do 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. For example, the growth trajectory for Scots pine will be quite different from that of Corsican pine even on the same site with the same management. 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.

Kerr and Jinks (2015) reviewed potential new species for the UK, starting with the 570 forest species listed in the CABI Forest Compendium (CABI International 2005) as having economic value in temperate regions. They considered further a subset of 240 based on climatic tolerance (predominantly minimum survival temperature) and their known performance in the UK. The subset was then ranked on the amount of research that had been carried out, the extent of current use in forestry, potential for producing wood products and the level of knowledge that was available at the time for providing objective advice. The species were split into three groups: principal species (species that are currently widely used for timber production); secondary species (species that have been planted on a much smaller scale that principal species but are reasonably well understood and have demonstrated their suitability in terms of stem form, growth rate and hardiness); and plot-stage species (species that demonstrated their suitability in trial plots).

It is feasible that this initial list can 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. These are considered below.

Known pests and diseases restrict future use of 6 of the 18 principal species, 4 of the 19 secondary species and 3 of the 32 plot-stage species. Unfortunately, species selection for a long rotation crop on the basis of pest and disease risk is problematic – this is convincingly shown by recent outbreaks that now constrain the use of several fast-growing species, e.g. Corsican pine, Japanese/European/hybrid larch and ash. Nevertheless, the risk of catastrophic losses due to a new disease reduces as the rotation length decreases so returns from SRF are less likely to be affected than from LRF.

One of the most relevant publications summarises the establishment and early growth of 44 native and non-native species on a variety of different site types in lowland Britain (Willoughby, et al., 2007) . 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 with the best performing species in the early phase being London plane (*P. x hispanica*) and black locust (*Robinia pseudoacacia).* 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, et al., submitted).

Volume growth of individual species is strongly influenced by the site conditions. The current 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., submitted). This is consistent with the findings of (Willoughby, et al., 2007). Matching species to the main site characteristics can be guided by the Ecological Site Classification taking account of Soil Nutrient Status, Soil Moisture Status and Climate, which covers average temperature and continentality.

Attempting to match species choice to future climate has been considered at length for the past two decades in the hope that future performance will be achieved by using species that grow well in a location that has a current climate similar to the anticipated future climate of the planting site.

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 rate and in addition the wood has a higher density than common conifers 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.

Three trade-offs should be borne in mind. These are generalisations and none is rigorously quantified:

- For a conifer species with a given genotype on a given site, it is generally the case that as volume growth increases, wood density decreases. However, this relationship is not one to one. Therefore, measures such as fertiliser application that promote a stand’s volume growth will usually decrease wood density, but proportionally this will be less than the gain in volume therefore this can increase net biomass.
- Increasing the spacing between stems generally increases the volume growth of the individual tree but the allocation of photosynthate changes resulting in a lower proportion of stem wood and higher proportion of branchwood and foliage. This may alter the system suited to collect biomass from site and the final conversion technology. The impact of spacing on growth as a whole is covered in Section 5.1.8.
- If a superior growth rate is achieved through an extended length of growing season, the risk of frost damage is likely to increase. In extreme situations this can kill the crop. If the crop has reached a harvestable stage, the impact may be acceptable but if no income can be realised from a young crop this will have a major financial impact. Less severe frost damage, which kills the terminal bud or shoot but not the lower stem, may result in a multi-stemmed tree; if the whole stem is destined for bioenergy, there may be a slight impact on harvesting efficiency. It is important to understand that some species have a superior growth rate not because of an extended growing season but because they make more efficient use of resources within a normal growing season. For those that are genetically adapted to the winter climate of that location, the potential risk of increased frost damage is not increased.

Tree species selection applies to the start of the bioenergy supply chain. Innovation would need to take place several years before planting in order that seed could be sourced and, if necessary, treated to break dormancy and ensure high germination. Usually seedlings are raised in specialist nurseries. Planting material is grown to match the expected site conditions and may take 1-3 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 may 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.

5.1.2.2 Status of innovation and key players

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., submitted) summarise a range of recent experiments and trials.

Key players are:

- Sourcing and pre-treating seed: Forestart, Maelor, Alba, Forestry England, Future Trees Trust
- Market confidence: ConFor, Forestry England, Forestry and Land Scotland, Tilhill, Woodland Trust

5.1.2.3 Potential impacts

Yield may be increased by up to 50% if the species combines fast growth and high density/calorific value. More typical increases may be 10-20%.

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, or possibly even exceed any volume losses. For example, sycamore may produce slightly less volume than Sitka spruce up to age 20[14] (e.g. 102 m^3 per ha vs. 124 m^3 per ha), but the oven dry wood density difference (e.g. 490 kg per m^3 versus 350 kg per m^3) would mean around 6.6 more oven dry tonnes of biomass standing in the sycamore, i.e. although the volume is about 18% less for the sycamore, the higher wood density results in a 13% relative increase in biomass.

Costs The main difference in cost is likely to come from the increased cost of planting material (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 big to be met from British seed sources and 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.

GHG emissions associated with establishment of the crop are likely to be reduced as these are typically related to the emissions at planting. Consequently, the increase in yield which is likely to result will reduce emissions per tonne harvested.

Environmental impacts will generally be positive. Species diversification is a well-established policy direction throughout the UK because it mitigates the risk of catastrophic damage in the event of pest and disease outbreaks and climate extremes. A wider range of species supports a more diverse range of dependent flora and fauna.

Any large-scale introduction of a non-native species must consider whether it could become invasive, impacts on water resources, and any propensity to harbour unwelcome pests.

Changing species to increase wood density is likely to be beneficial in terms of handling and transport efficiency.

5.1.2.4 Issues associated with implementation

Specific barriers.. UK forestry is based on a highly efficient system of growing, processing, and marketing a relatively small range of species and products and there is likely to be considerable reluctance and inertia to a change in species. Even if bioenergy is a co-product of the main timber

[14] In this example the sycamore has a yield class (volume productivity) of 10 and the Sitka spruce has a yield class of 16. This would consistent with planting on a good suitable site.

output, investors (such as pension funds) find it difficult to commit to a species that does not have a growth and yield curve or reasonably well-known product outturn. This conservatism tends to feed back to nursery growers, who prefer to grow tried and tested species that can be produced efficiently to known markets; they are likely to be reticent to invest in large-scale production of alternative species without some assurance that demand will continue. In practice therefore a shortage of suitable seedlings to plant may be the first tangible barrier. The limited supply of good quality seed, especially from UK sources, may limit the use of some species.

Stakeholder interviews indicated several related points that would need to be addressed to ensure a change in species choice to supply a bioenergy end market. The current grant structure was felt to place restrictions on the opportunities to experiment with innovative species. There is a perceived barrier due to the resistance in the public and environmental NGOs towards non-native species and in particular to eucalyptus which has had negative environmental impacts in other countries. Stakeholders also noted that there is a perception that there is a risk in growing trees *just* for bioenergy. Uptake could be encouraged if species with rapid early growth and flexibility around site type are available and are accompanied by supporting information on the necessary site conditions and initial spacing.

Changes required. Potential ways to overcome resistance to species change could include: contract growing of nursery stock; demonstration forests of reasonable scale, monitoring of environmental impacts, assessments of invasiveness, and collaborative approaches towards the introduction of novel species. If a wider range of species was accepted by the sector, nursery practice may have to be modified for some species but there is no particular reason why later process steps would have to change significantly. For novel species destined for a dual bioenergy-timber end use, wood and timber properties would need to be understood.

Likely reception. Experience over the past 5 years suggests that the large-scale industry is very focussed to continuing with existing species despite the undeniable evidence of major disease impacts to commercial UK species (e.g. Corsican pine, and larch). Nevertheless, some investors are willing to accept potentially smaller yields or a less certain long-term return on investment to mitigate +risk and/or encourage biodiversity. Private landowners of large estates, particularly those with a very long-term perspective, may be the most receptive to species change. If exotic species rather than native species were used extensively, the reception by some stakeholders (e.g. the public, and environmental NGOs) is likely to be negative. One stakeholder commented that exploring the use of new species is worthwhile. For example, in Cornwall some eucalypt species are growing well with a first thinning after 4 years which has generated local interest and participation in further planting of eucalypts.

5.1.3 Provenance choice

5.1.3.1 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. Recently a common response to anticipated climate change is to choose a provenance from up to 5 degrees of latitude further south [(Barsoum, 2015)]. If this approach is extended too far however, this can increase the risk of frost damage so the net benefit decreases.

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)].

Provenance choice applies at the same point as species choice, i.e. planting stock preparation.

5.1.3.2 Status of innovation and key players

Innovation status. The principle is well established for both conifers and broadleaved species but the TRL status varies from 9 to 5 depending on species. For the main UK commercial conifer 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; TRL is 5. For still 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.

The main players Operational use of provenance choice to increase volume growth is practiced by management companies, e.g. Tilhill, and by managers of the national forest estate. Forest Research is responsible for almost all long-term provenance trials, especially of conifer provenances. More recent collaborations of private land owners under the umbrella of the Future Trees Trust have taken greater responsibility for establishing provenance trials of broadleaved species.

5.1.3.3 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% 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 (D^2H) 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.

Environmental impacts are likely to be minimal, e.g. (Nisbet, et al., 2011), (Vanguelova & Pitman, 2011).

5.1.3.4 Issues associated with implementation

Specific barriers. The barriers are likely to be limited to ones associated with sourcing the seed and ensuring its quality.

Changes required. For some highly productive provenances already growing in the UK, seed collections could be made more efficient. If seed has to be imported, commercial agreements could be established to ensure sufficient good quality seed.

Likely reception. Apart from minor concerns if price is increased, the likely reception should be neutral or positive.

5.1.4 Genetic improvement

5.1.4.1 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 (rotation lengths in SRF are shorter so the benefits can be realised in a shorter time scale).

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.

5.1.4.2 Status of innovation and key players

Innovation status. 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 contribution of high wood basic density, leading to higher energy density. These species have been established in trials by FR 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. This increased timber production is likely to be linked to increased production of smaller dimension material that could utilised for bioenergy, but may not deliver as large an increase as use of species specifically selected for characteristics which would help to maximise bioenergy production.

Main players. Forest Research, Future Trees Trust

5.1.4.3 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 5 the productivity over generations, i.e. in Brazil and China [(IBÁ, 2015) and (Xie, 2015), respectively]. Particularly for SRF, a test could be established after 2 years, with assessments and selection after 5 years; in this way improved material could be available after 7 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 Russel 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 5 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.

Environmental impacts. Assuming that the species is matched to the site, environmental impacts are expected to be generally beneficial and similar to those of unimproved plants.

Stakeholders commented on the potential for genetic modification to create a range of benefits, not only for yield and crop characteristics such as pest and drought resistance and management benefits, but also for the end products' characteristics, such as wood sugar content.

5.1.4.4 Issues associated with implementation

Specific barriers:. The time to produce planting stock for deployment is a barrier. Time is less of a challenge if genetic selection and breeding is applied to species with inherently fast growth rates that will be used for short rotation bioenergy forests on better quality ground.

Changes required. A re-evaluation of benefits of genetic improvement in the context of bioenergy markets may be justified.

Likely reception. Uptake by the sector is likely to depend on the extent of proven productivity gains in relation to the additional cost of the planting stock. One private sector manager noted that genetic improvement (e.g. of Sitka spruce) could offer some potential to improve growth and went on to say that clients do not have a problem with genetic modification provided it is proven to provide returns. Reception by the public will probably depend on the species; native species such as common alder and perhaps sweet chestnut are likely to be more readily accepted than eucalyptus.

5.1.5 Mixed species stands

5.1.5.1 Description

This innovation involves the increased use, when establishing new LRF, of species mixtures chosen with a potential bioenergy market in mind. 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).

This innovation would mainly apply to the creation of new woodlands and would be introduced at the planting stage.

5.1.5.2 Status of innovation and key players

Innovation status. TRL is 5-9 depending on species.

Main players. 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.

5.1.5.3 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 FR 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.

Environmental impacts There could be positive impacts for GHGs, environment and resilience. (Jonsson, et al., 2019), using data from a nationwide forest inventory covering an area of 230,000 km^2, showed that relative abundances of commercial tree species in mixed stands strongly influence the potential to provide ecosystem services. The mixes provided higher levels of ecosystem services compared to respective plant monocultures (overyielding or transgressive overyielding) in 35% of the investigated cases, and lower (underyielding) in 9% of the cases. Furthermore, the relative abundances, not just species richness per se, of specific tree-species mixtures affected the potential of forests to provide multiple ecosystem services.

5.1.5.4 Issues associated with implementation

Specific barriers. The main barriers to adoption are inertia and tradition but policy and guidance could be improved to help overcome this and positively encourage changes in practice. This mainly applies to conifers as many broadleaves woodlands many are planted in mixture due to the changes to grant scheme incentives in the 1980s and 1990s.

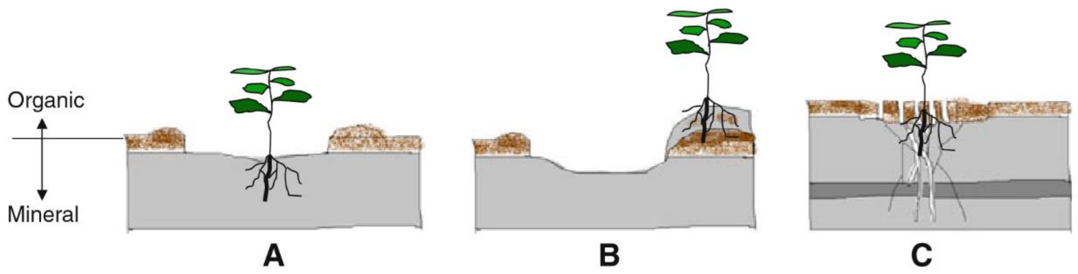
Likely reception There may be a slight resistance to implementation because of the slightly greater complexity of management compared to a single species stand. This is borne out by one stakeholder who commented: introducing a nurse species would help to reduce the financial risk associated with multi-species stands (in comparison with planting an entire area for biomass), however, it is difficult to find a nurse species which works effectively. Another commented that the use of nurse crops (e.g. Norway spruce with oak) are routinely unsuccessful, often due to poor management, such as a lack of thinning.

5.1.6 Soil preparation by ripping

5.1.6.1 Description

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 is a mechanical preparation method used for dry soil and for soils that have a deep compacted layer that restricts root growth and plant development (e.g. (Moffat & Bending, 2006)). It is also occasionally used to overcome surface compaction. Figure 5-1 illustrates ripping's reduced impact on upper organic layers compared to that of scarification and mounding.

Figure 5-1: Schematic description of three types of mechanical site preparation



Three types of mechanical site preparation and their main effect on soil structure: scarification (**A**), mounding (**B**) and ripping or subsoiling (**C**). *Dark grey area* below mineral soil represents hardpan in **C**. Normal planting spots are illustrated with a seedling. For **A** and **B** some authors recommend planting at the trench-berm interface (e.g. (Boateng, et al., 2012))

Ripping encourages deeper root development than any of the other common 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. The timing can be important, as some methods should be carried out only during dry periods to prevent re-compaction of the soil.

Deep ripping would be implemented during ground site preparation

5.1.6.2 Status of innovation and key players

Innovation status: Deep ripping is a familiar technique in arable systems so in agricultural systems TRL is 9. It is also used in the restoration of degraded land such as mine spoil. In forestry ripping has been used to break up compacted layers deep in the soil profile. This was relatively common during the large-scale afforestation programmes of last century but currently is not used widely in the UK so TRL is closer to 6. The basic technique needs to be refined and evaluated for impacts on soil carbon, GHG emissions, and diffuse pollution as well as an assessment of the its impact on bioenergy production and costs.

The main players are large management companies in both the private and public sectors, e.g. Tilhill, Euroforest, and Scottish Woodlands as well as Forestry and Land Scotland and Forestry England.

5.1.6.3 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. Target soils for short rotation forestry should be tested to quantify the effects.

Environmental impacts. Negative effects are likely to be minimal as one of the postulated benefits is that ripping greatly reduces loss of soil carbon because of the much lower degree of soil disturbance (see Figure 5-1). The net effect on environmental impact should be evaluated specifically to take account of the short term on soil disturbance and the longer-term impact on growth. For example, as articulated by one stakeholder, an advantage of ripping may be that it causes less soil carbon loss, but the losses caused by alternative methods such as ploughing may be offset by a reduction in weed control chemicals and operations.

5.1.6.4 Issues associated with implementation

Specific barriers Machine availability. To achieve the greatest benefits, ripping and planting should be combined which makes management more challenging. Stakeholder feedback pointed out that some of the most suitable land for new planting (e.g. peaty gley soils) would be unsuitable for ripping whereas the land most suited to ripping tends to be ground capable of supporting arable crops and here ripping also risks damaging clay tile drains.

Changes required. The technique should be re-evaluated to develop a full understanding of the costs and benefits in present circumstances, especially the impact on soil carbon and carbon sequestration in the trees.

Likely reception. The use of innovative ground preparation techniques was mentioned by stakeholders, which suggests that it may have a positive reception.

5.1.7 Direct seeding

5.1.7.1 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 the cultivation of seedlings or cuttings in a nursery; the planting stock and subsequently planting at the field site are both expensive.

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.

Status of innovation and key players: TRL is 7 for both broadleaved species on lowland sites and conifer species in upland sites.

5.1.7.2 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 seedling 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 natural regeneration this is managed by each tree producing 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.

Environmental impacts: Direct seeding potentially allows a significantly greater density of seedlings to be established, reducing the time to canopy closure, thus reducing the requirement for herbicide inputs. The woodland is likely to be biodiverse.

5.1.7.3 Issues associated with implementation

Specific barriers to direct seeding are availability of the higher quantities of seed needed, predation by birds and small mammals, and lack of familiarity and guidance.

Likely reception. Direct seeding - on ad-hoc basis (e.g. where ash is being felled or where targeted felling has occurred) - could be used to fill gaps in the canopy while offering an opportunity to diversify into biomass production. In an agricultural situations direct seeding is expected to be well received because of the similarity with agricultural crops in terms of the equipment needed and techniques needed and as noted above establishment costs using direct seedling may be lower than planting. Because of the more natural appearance and wider bio-diversity of the resultant woodland, the system is likely to be supported by the public and NGOs.

5.1.8 Changing initial spacing between trees

5.1.8.1 Description

The current standard spacing between trees for commercial conifer 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. For example, closer initial spacing could be combined with early and/or additional thinning to remove a biomass crop after which the remaining trees could be managed as usual for a timber crop. 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. In the view of one stakeholder initial planting spacing could reduce from 2.0 m to 1.5 m; at spacings of around 1.0 m or less, there will be issues with maintenance, weeding etc.

5.1.8.2 Status of innovation and key players

TRL It is difficult to judge the TRL exactly as 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. However, there are many historical examples of spacing trials that could be considered. On this basis a TRL of around 6 or 7 would appear appropriate.

Key players Forest Research are active in the field of silvicultural research, including the impacts of initial spacing of trees. A number of private forest estates have also undertaken limited work on the subject.

5.1.8.3 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 and 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 if you were maximising 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 trees in the closer spaced stand are around 50% smaller.

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

Environmental impacts Closer spacing would generally result in higher carbon stocks per hectare. However, any increase in operations and number of seedlings would likely generate a small increase in GHG emissions. There could be some other environmental impacts, but these are not likely to be large, given the relatively limited range in initial spacings likely to be proposed.

5.1.8.4 Issues associated with implementation

Specific barriers. Given that changing initial planting spacing is effectively altering the intensity of known forest management, the barriers are likely to be minimal. As noted by one stakeholder: successful uptake is likely to require information on how species dependent the optimum spacing is for bioenergy supply.

Changes required. There may need to be limited changes in practice during planting, for example mechanised planting could be considered. Further down the line harvesting techniques and technology designed for dealing with harvesting of closer spaced stands of trees might also need to be considered.

Likely reception. Given that the desired outcome of changing planting spacing would be to increase supply to bioenergy markets, it is likely that suppliers would receive the change favourably. However, as noted, if the size and characteristics of the timber produced are very different this may lead to some challenges for suppliers.

5.1.9 Fertilising crops using anaerobic digestate or wood ash

5.1.9.1 Description

Digestate from anaerobic digestion ('AD'), 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. Success of this innovation would both be dependent on sensitive specification and close control in practice.

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

AD 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) an 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).

5.1.9.2 Status of innovation and key players

Innovation status TRL is difficult to gauge and could range from 1 - because the innovation has not been investigated for forest crops – to 6 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. Trials are required to clarify the site characteristics and circumstances where increases in yield justify the cost of application. Factors to be investigated include application regimes and protocols, the form (concentration for AD; granulated or not for ash), and environmental impacts in forestry situations. Production of anaerobic digestate from food waste is now common practice. A British Standard has been developed for production of an AD 'quality' organic fertiliser from separated ('uncontaminated' and source identified) waste, primarily for sale to the agricultural sector. Material that does not comply with the standard may still be available as a fertiliser – and possibly at low cost - although, as it is still classified as a 'waste', strict licensing approvals are required prior to application.

Whilst application of organic (and inorganic) fertilisers is common – and usually necessary – in agricultural production, this is not the case within forestry. Firstly, there are no proven demonstrations of AD to forests and secondly the UK Forest 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. This is a consequence of forestry as a much less intensive land use, closely associated with natural ecosystems and to their landscape settings, whether in lowland or upland. Use of fertilisers, especially AD, would <u>definitely</u> have a major, and probably prohibitive, 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.

5.1.9.3 Potential impacts

Yield 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 / 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.

The GHG emission effects would appear to derive primarily from increased growth rates and CO_2 uptake.

Environmental impacts Considerable care would be needed to avoid adverse environmental impacts, particularly nitrification of surface and ground water. This issue would apply not only in the Nitrate Sensitive areas that cover much of lowland England but in many catchments throughout the UK.

5.1.9.4 Issues associated with implementation

Specific barriers The main barriers to adoption are likely to follow from environmental concerns, not least limits on the available nitrogen that can be applied to land as fertiliser. In forestry this is generally limited to 1,000 kg of total nitrogen per hectare as a one-off application, and then only if shown to be necessary for ecological improvement. As stated, there are further restrictions with NSAs. The key is that the system must be well specified and controlled in practice (which costs money).

It is appropriate to note significant past experience of using sewage sludge (undigested, digested, and pelletised) to forest land as research experiments and also to degraded land, particularly mining spoil, in both experiments and operational practice. These indicate that there would be barriers to the use of AD by the environmental regulators and the public.

Acceptability to the UK Forestry Standard would have to be considered.

The farming sector – the supplier - already has a good track record of using and controlling applications of organic fertiliser to land for cropping or grazing although this is in the form of cattle slurry, and in some instances sewage sludge. These carry not dissimilar risks and regulation to the use of AD so there is a helpful model already in place if AD were to be extended to forest land.

Changes The changes to current practice would be manageable in the SRF context given good practice and, ideally, use of farming practice and machinery for application.

Likely reception Social acceptability is anticipated as a manageable issue within the farming landscape, but probably not within the forest landscape. *Note that AD can smell strongly of sewage.*

5.1.10 Remote sensing for crop monitoring and management

5.1.10.1 Description

A range of remote sensing techniques could be applied to assess growth rates and possibly bioenergy yield. Increasingly advances (and cost reduction) in satellite imagery, LiDAR and UAVs (drones) may provide a way of monitoring woodlands. Torresan (Torresan, et al., 2017) review forestry applications of UAVs in Europe and identify uses; although presently the primary function usually serves inventory purposes, other uses exist in identifying spatial gaps, and forest health. Goodbody (Goodbody, et al., 2017) suggest such systems can be used in the identification of residual material following selection harvesting. In addition, in remote sites, data captured by airborne sensors could be used to monitor growth, in particular early growth up to canopy closure, or to identify neglected woodlands or health issues. Analysis of the spectral data and point clouds is an ongoing developmental process, leading to more applied use as resolutions improve. 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, efficiency of site operations to optimise thinning, felling and extraction, early identification of pest and disease, and asses the benefits this could bring..

5.1.10.2 Status of innovation and key players

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 the key UK players in the development of bespoke forestry applications.

5.1.10.3 Potential impacts

Yield. The direct impacts are likely to be limited.

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

Environmental impacts. Overall modest benefits might be anticipated through improved operational efficiencies and more rapid interventions, e.g. to control pests and diseases.

5.1.10.4 Issues associated with implementation

Specific barriers - The main barrier is providing a robust system or product at an attractive price. The recent provision of analysis-ready data free of charge through pan-Government agreements is leading to a significant change in affordability.

Changes Costs of some sensors and datasets must reduce.

Likely reception - The maps are readily accepted but commercial use is highly dependent on cost and currency of the products.

5.1.11 Manipulating cut-off diameter

5.1.11.1 Description

At harvesting, to 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. 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.

5.1.11.2 Status of innovation and key players

Innovation status. TRL is 9 - the importance of cut off diameter is already a well understood issue at ‘the sharp end’ of the harvesting operation involving owners, merchants, contractors and primary processors - but its integration in systems producing both a timber and a biomass crop is closer to TRL 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 at 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 are management companies, private sector foresters, and managers of the national forest estate.

5.1.11.3 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.

Environmental impacts If the cut-off diameter is larger and this makes residue removal economically viable, the resultant increase in removal of nutrients may in the long term have an impact on site sustainability.

5.1.11.4 Issues associated with implementation

Specific barriers Although consideration of cut-off diameter issues is already adopted, its importance needs to be considered in any novel round wood-based harvesting system. Once embedded in a new system it should readily be adopted, subject to practicality. The forest harvesting sector – the supplier - already has a reasonable track record of adopting practical cut-off diameters and understands the possible consequences of 'getting it wrong' on any particular site. However, achieving the ideal in practice can be quite difficult.

Changes to current practice would be minimal, other than those inherently involved in any new harvesting system.

Likely reception is expected to be neutral or positive.

5.1.12 Removal of stump to ground level

5.1.12.1 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.

5.1.12.2 Status of innovation and key players

TRL is around 2 mainly because an efficient system for cutting close to ground level and handling the stumpwood has not actually been developed.

Key players are not established.

5.1.12.3 Potential impacts

Yield The increase in yield is estimated on the basis of FR 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 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.

Environmental impacts. There are likely to be several effects, some positive and some potentially negative so the overall impact may vary from site to site. Risks would be greater soil damage so mitigating actions, such as additional brash mats might be needed on some sites. The lower nutrient content of the stump (compared to the fine branches and foliage) means however that the impact on site nutrient sustainability is likely to be minimal. An additional benefit may be that the site would look neater and may be more acceptable from a visual point of view.

5.1.12.4 Issues associated with implementation

Specific barriers are mainly technical. More widespread **adoption** requires widespread availability of suitable harvesting heads, experience of their use, and conversion of existing machinery – which would probably happen over 3 – 5 years as heads are replaced over time. Shear heads are just starting to appear in UK forestry and this trend is expected to continue anyway. A second process that would promote adoption would be to incorporate this technology within a bespoke forestry biomass system, along with other individually marginal, but collectively cumulative process improvements.

Changes required. Technical development and evaluation would be needed

Likely reception. Assuming that an efficient system is available, this would be readily accepted by practitioner. It would involve dissemination of evidence of the effectiveness and availability of effective shear heads (or future alternatives), preferably coupled with other system developments such as bunching technology and the biomass recovery market. Because of woods excellent chemical characteristics for large scale combustion this material is likely to be attractive to end users.

It was mentioned by stakeholders that the cost of stump extraction made it difficult to justify, especially as the characteristics of the material obtained did not meet the specifications required by many (current) end users owing to the presence of inclusions.

5.1.13 Residue removal

5.1.13.1 Description

The innovation would be 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.

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.

5.1.13.2 Status of innovation and key players

Innovation status TRL is 7. Removing residue – or 'brash' in forestry terminology - 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. Also on very steep slopes manual felling is still the only option, followed by extraction of the whole stem by cable crane to forest roadside; in this situation, residue removal is a consequence of whole tree extraction. 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 is needed if this innovation is to be successful.

Key players are management companies, private sector foresters, and managers of the national forest estate.

5.1.13.3 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 / 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.

Environmental impacts. Environmental sustainability is an important consideration for two main reasons. The main concern is the nutrient sustainability especially of nutrient poor upland sites because of the disproportionately high nutrient content of the fine residues; this could be alleviated by compensatory fertilisation (e.g. with wood ash and/or AD) and is less likely to be an issue on more fertile lowland sites. Increased risk of soil damage is a second consideration. Unless care is taken to leave sufficient brash to form brash maps, sensitive soils may be at risk of compaction or erosion which could create down slope water pollution. On the other hand, there may be a marginal environmental benefit because the post-harvesting landscape is more aesthetically pleasing.

5.1.13.4 Issues associated with implementation

Specific barriers The main barriers are the potential adverse environmental impacts, particularly soil nutrition, erosion and watercourse siltation that influence both harvesting practice and site suitability (these factors are widely covered by current regulation and good practice). Also, the material obtained from brash harvesting is generally relatively high in ash content, and not suited to many current applications, particularly pelleting (this can be handled by designing end use equipment specifically to handle such material). As noted by one stakeholder: the main question is how much removal is appropriate? There is a reluctance to remove all brash from a site harvested by machinery since a ground covering of brash can help to protect soils as machines manoeuvre on site. It is unclear how what level of residue or brash removal represents the 'right' amount in terms of maximising product without compromising the future viability of the site. OR, is it possible that in some circumstances, carbon stocks can increase as a result of removing biomass? Another stakeholder pointed to the logistical issues – the time taken to collect brash is much longer than for logs and chips since brash is harder for the forwarder (machine) operator to manage; this complication (and time constraints) generally results in some brash being left behind in the woodland.

Changes required There are two main strands to supporting changes to current practice. Firstly, residue recovery should be integrated within the silvicultural and harvesting system from the outset, as opposed to as an end-of-rotation 'add on'. This could affect, for example, aspects such as species and provenance choice, initial spacing (and therefore establishment costs) and rotation length. Secondly, UK forestry harvesting capability needs to be developed to most efficiently clear crops and present biomass in a form most suitable for the downstream biomass user's business. These systems are likely to be an imaginative extension of current harvesting and extraction machinery options (see Section 5.1.15 on harvesting technology).

Likely reception Social acceptability is not anticipated as an issue providing that systems are used in an appropriate landscape context and where they are not themselves a threat to the environment.

5.1.14 Stump and root removal

5.1.14.1 Description

To utilise as much of the stump and attached root system as possible within a silvicultural, harvesting and utilisation system. This innovation is distinct from 'Removal of stump to ground level (see 5.1.12). Stump and root removal was trialled in the UK some years ago but has not become an established practise 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.

This innovation affects harvesting. It might also be introduced at the same time as residue removal (see Section 5.1.13).

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.

5.1.14.2 Status of innovation and key players

TRL is 7-8. Systems for removing stumps and attached roots have been trialled in the UK.

Key players were mainly private sector management companies.

5.1.14.3 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.

Environmental impacts can be considerable, e.g. (Walmsley & Godbold, 2010), which has led to Forestry Commission guidance covering ground damage, soil carbon loss, nutrient sustainability and acidification (Nisbet, 2009) and a general presumption against stump harvesting.

5.1.14.4 Issues associated with implementation

Specific barriers In this case, the barriers are mainly environmental and also public perception. There is also some anecdotal evidence of practical problems associated with stump and root harvesting for bioenergy, possibly due to contamination. As with residues (Section 5.1.13), suitably designed specialist conversion equipment to make use of this material could help to alleviate some of these issues. As pointed out by one stakeholder, stump removal comes with several challenges: weed growth following removal can be hugely problematic; attempting to restock post-removal can also be very difficult; the process of stump removal significantly reduces soil carbon through disruption of the soil horizons; the machines use large amounts of diesel leaving question marks over the sustainability of the practice; and the irregular shape of stumps and their tendency to hold soil makes for inefficient haulage operations (relative to shredding on site prior to removal). Another private sector stakeholder commented that stump removal requires a 360° excavator to remove and shake soil from a whole stump; while this is feasible for new highways/railways, in a woodland setting the soil structure will be negatively impacted.

Changes to current practice. Relevant machinery is needed to pull out and then remove stumps from site. Environmental issues would need to be re-examined and clear guidance issued, linked to careful discussion with regulators and communication.

Reception is likely to be negative because of environmental concerns therefore contractors may be reluctant to invest in the expensive equipment.

5.1.15 Harvesting technology

5.1.15.1 Description

This innovation would involve 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. 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. To quote one stakeholder "Shears are great for biomass products as they cut down on labour time. A shear that goes directly onto a forwarder to prevent the need for material to be 'double-handled' can cope with material up to around 30 cm in diameter With this kind of innovation lots of brash in forestry/woodland environments could now be forwarded to the roadside and on to market (whereas it would have been left to rot in the past)." A 'buncher' is also available which allows multiple trees to be picked and cut at the same time, increasing efficiency.

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

5.1.15.2 Status of innovation and key players

Innovation status TRL is 2. Forest machinery development is constant, although tending towards 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.

5.1.15.3 Potential impacts

Yield Increase in yield can be achieved through harvesting more of each tree, such as poles with tops, or whole trees.

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 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.

Environmental impacts There may be an improved site appearance if less residue is left on site. Also, well designed equipment should reduce fuel consumption and maintenance requirements.

5.1.15.4 Issues associated with implementation

Specific barriers The system must work and be practicable in use in order to sustain the development, testing and refinement of a new system. When forestry professionals and contractors see inherent advantages of an innovation, adoption can follow fairly quickly. The forest harvesting sector already has a good track record of both generating and adopting practical innovations.

Changes The degree of changes to current practice would depend on the system concerned, although (arguably) evolution is more likely to make progress in the shorter term than revolution.

Likely reception Social acceptability is not anticipated as an issue in this case.

5.1.16 Other innovations

Additional technical innovations that stakeholders suggested would be desirable were:

- Exploitation of thinnings from natural regeneration conifer 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 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.

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 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 (currently 15% of broadleaf increment and 50% of conifer). Please note that these figures have not been confirmed by official statistics and may refer to anecdotes or a particular geographical region.

- 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 operation with relatively small quantities of widely distributed biomass. It was suggested that joined up working between different sectors with relatively small 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 have been 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.

5.2 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 5.2.1)
- trees in combination with other plant crops (Sections 5.2.2 and 5.2.3)

5.2.1 Trees in combination with poultry or grazing animal

5.2.1.1 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.

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 to assess the impact on GHG emissions, as well as the impact on bioenergy production and costs.

5.2.1.2 Status of innovation and key players

Innovation status. 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.

The main players Moy Park is the UK's biggest supplier of free-range chicken and eggs; 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.

"At Sainsbury's, we've raised £6.9m for the Woodland Trust, primarily through free-range and organic egg sales. But woodland habitats can also mean free-roaming hens – for top-quality eggs."

5.2.1.3 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 be 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.

Environmental impacts are generally positive. Adding trees to a pasture will increase the biodiversity, and will bring many of the other benefits of trees, such as increased soil carbon, and, in certain circumstances, soil stabilization or flood water control. Individual trees distributed within a field are likely to be less GHG efficient to harvest per tonne of wood than clearfelling a forest. Also trees grown in isolation produce a higher proportion of side branches than those deliberately grown in close proximity in a forest. This will produce a greater proportion of bioenergy feedstock, and less for sawlogs, which gives a lower overall GHG efficiency than equivalent forest trees. However, since the counterfactual is likely to be a grazing or free range pasture with no trees, in comparison with this the impact is significantly more carbon sequestered, and a significant net GHG benefit.

In addition, it is thought that chickens are less stressed when there is some overhead cover, and pigs are known to suffer from sunburn and sunstroke, so introducing shade can help to prevent this.

5.2.1.4 Issues associated with implementation

Specific barriers. Free-range animal production is highly competitive, especially poultry and pigs which are not subsidised, so any impact on profitability of the whole system will be a significant barrier. Woodland grant aid does not cover widely spaced trees typical of most agroforestry systems in England and Wales. There may be a perception that management will be significantly more complicated although several guides have been produced by the Woodland Trust on incorporating trees with free-range poultry or livestock. Ways to increase this agroforestry system should be investigated. In the case of combinations involving grazing animals, a stakeholder commented that more information relating to the pros and cons of agroforestry based on long-term studies is needed to assess whether it is economically viable.

Changes required. Awareness and education, including demonstrations, of successful agroforestry options would be helpful. Uptake may be encouraged by public pressure for higher animal welfare plus support for these industries to play their part in climate change mitigation. The Woodland Trust's view would be interesting.

Likely reception. Difficult to predict. Provided it is cost neutral, this option might be well received by some of the big players who are very aware of their environmental impact and PR. One stakeholder noted that there is uncertainty about what those promoting agroforestry are trying to achieve. A clearer message is needed regarding expected results if momentum is to be gained; at the moment is us used as a 'tick box', rather than detailed way of increasing biomass supply and is not always efficient, compared to conventional forestry.

5.2.2 Trees in combination with other plant crops

5.2.2.1 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 covering in the following section (5.2.3)

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).

5.2.2.2 Status of innovation and key players

Innovation status. TRL 3.

The main players Research institutes, e.g. Cranfield.

5.2.2.3 Potential impacts

Yield UK experience is very limited but de (de Jalon, 2018) compared poplar + 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 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.

Environmental impacts are generally positive though this assumes that the species choice is ;appropriate. Impacts on GHG emissions, above ground carbon sequestration, soil erosion losses, nitrogen surplus and phosphorus surplus were modelled by de (de Jalon, 2018); the agroforestry (and forestry) systems increased C sequestration and decreased GHG emissions and surpluses of nitrogen and phosphorus.

5.2.2.4 Issues associated with implementation

Specific barriers. Woodland grant aid does not cover widely spaced trees typical of most agroforestry systems in England and Wales. Given the current extreme uncertainty in the agriculture sector, owners are very unlikely to commit to a cropping system that limits their flexibility. There may be a perception that management will be significantly more complicated. There are no operational examples of commercial scale systems to provide case study information.

Changes required. The crop combinations would have to be significantly more productive and profitable than the current crops when grown individually, e.g. if the tree crop produced an additional highly profitable product such as honey, fruit or nuts. Alternatively, the environmental benefits, e.g. to water quality, could be a deciding factor in some circumstances.

Likely reception. Most land owners are likely to reject this option - defined areas of new woodland (SRF or LRF) would have less impact on their future management options so might be preferable to intercropping.

5.2.3 Trees with ground layer biomass crop

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

5.2.3.2 Status of innovation

Innovation status. 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.

5.2.3.3 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’.

Environmental benefit. There may be pest and disease, temperature regulation and other advantages for the crop components and, in the case of forestry, a lower herbicide requirement.

5.2.3.4 Issues associated with implementation

Specific barriers An important factor is likely to be the quality of land required for the agronomic component, although such land is already within scope of high yielding SRF. There may be also be potential for using species of certain rushes or sedges (or others) on poorer quality, softer ground combined with longer rotation forestry as wide spacing – as was used for the poplar matchwood industry.

Changes required The main requirements for adoption would be firstly selection of an appropriate field layer candidate (a more shade tolerate ‘C3’ grass perhaps) and design of a suitable cultivation and harvesting specification to utilise current equipment in use.

Likely reception Given the current extreme uncertainty in the agriculture sector, owners are very unlikely to commit to a cropping system that limits their flexibility. Social acceptability is not anticipated as an issue providing that species are used in an appropriate landscape context and where they are not themselves a threat to habitats.

5.3 Summary

A summary of the key technical innovations identified, their technology status and an initial assessment of their potential impact on the GHG emissions and costs for the production step they apply to and their impact on overall production costs and GHG emissions is given in Table 5-1.

Table 5-1: Summary of forestry innovations

Feed-stock	Pro-cess step	Innovation	TRL	Impact on: Yield	Process step: Cost	Process step: GHG	Overall: Cost	Overall: GHG	Other benefits
LRF-all SRF-all	1	Species selection	5-9	↑↑↑↑ ↑↑↑↑	↑↑		↑		↑↑↑
LRF-all SRF-all	1	Provenance choice	5-9 6	↑↑ ↑↑	↑↑		↑		↑↑
LRF-all SRF-all	1	Genetic improvement	2-7 1-7	↑↑↑ ↑↑↑	↑↑↑		↑		↑↑↑
LRF-all	3	Mixed species stands	5-9	↑↑↑	↑↑		↑↑		↑↑↑
LRF-all SRF-all	2 or 4	Soil preparation by ripping	9	↑↑↑	↑↑↑		↑		↑↑↑
LRF-all SRF-all	3	Direct seeding	7	-	↑↑ ↓		↑ -		↑↑
LRF-all SRF-all	3	Changing initial spacing between trees	6-7	↑↑ ↑↑↑	↑↑		-		-
LRF-all SRF-all	3	Fertilising crops using anaerobic digestate	1-6	↑ ↑↑	↑↑		↑↑		↑
LRF-all	6	Remote sensing for crop monitoring and management	6	↑	↑		-		↑
LRF-C	5 and 6	Manipulating cut-off diameter	7	↑↑	-		-		-
LRF-all	6	Removal of stump to ground level	2	↑	↑↑		↑		↑
LRF-C	5 and 6	Residue removal	9	↑↑	↑↑		↑↑↑		↓ or ↑
LRF-C	6	Stump and root removal	7-8	↑↑↑	↑↑↑				↓↓↓ or ↑
LRF-all SRF-all	5 and 6	Harvesting technology	2	?	?		?		?
New	1(->6)	Agro-forestry (trees + poultry or grazing animals)	2-7	↑	↑↑		↑↑		↑
New	1(->6)	Agro-forestry (trees + crop)	2	↑	↑↑		↑↑		↑

Key for Table:

Impacts

-	None or very small impact	?	Uncertain (
↑	Small increase (0 to 5%)	↓	Small decrease (0 to 5%)
↑↑	Moderate increase (5 to 10%)	↓↓	Moderate decrease (5 to 10%)
↑↑↑	Significant increase (over 10%)	↓↓↓	Significant decrease (over 10%)

	Feedstocks		**Process steps**
LRF	Conventional long rotation forestry	1	Planting stock preparation
SRF	Short rotation forestry	2	Land preparation
-C	coniferous	3	Planting and establishment
-B	broadleaved	4	Cultivation and maintenance
New	Novel approach	5	Thinning (forestry only)
		6	Harvesting and collection
		7	Post-harvest: storage and pre-processing on site
		8	End of life/site reversion

TRL

1	Basic research	Principles postulated & observed, no experimental proof available
2	Technology formulation	Concept and application have been formulated
3	Applied research	First laboratory tests completed; proof of concept
4	Small scale prototype	Built in a laboratory environment
5	Large scale prototype	Tested in intended environment
6	Prototype system	Tested in intended environment close to expected performance
7	Demonstration system	Operating in operational environment at pre-commercial scale
8	First-of-a-kind commercial system	Manufacturing issues solved
9	Full commercial application	Technology available for consumers

Table 5-2: Summary of innovations to address specific barriers

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution	Potential impact on cost of production
Costs	Cost of operations compared to the value of products	• 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	• 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)	Very high High for some spp. Medium Medium Medium High after application Low Medium High Medium Medium/low Low

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution	Potential impact on cost of production
Costs	Cash flow	• Contracts between grower and end-user with staged payments	• 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)	High provided planting is not restricted to poorest quality land High Medium/low Medium
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	
Costs	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	
Costs	Scale of operation	• Land-owner cooperatives • Improved logistics		

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution	Potential impact on cost of production
Access	Access for harvesters, large equipment	• Review equipment developed in countries with more mature bioenergy culture	• Harvesting technology suited to smaller scale operations	Medium
Access	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 conifers cf. broadleaved species), stem diameter, proportion of leaves/needles, time of felling.	
Feedstock properties	Moisture content	• In-wood passive utilisation of waste heat		
Feedstock properties	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 infrastructure /resources	Availability of specialized, expensive machinery		• Integrated harvesting systems • Harvesting technology suited to smaller scale operations	High Medium
Availability of infrastructure /resources	Availability of trained labour force and contractors		• Extension of technical training to include bioenergy	Medium
Availability of infrastructure /resources	Availability of efficient feedstock drying equipment	• Review equipment developed in countries with more mature bioenergy culture		
Availability of infrastructure /resources	Availability of planting material	• Confidence in nursery sector that there is a medium -long term market	• May need additional research to develop efficient systems for novel species	

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution	Potential impact on cost of production
Logistics	Bulky material expensive to transport and store	• In-wood drying • Compaction of residues and chips		
Logistics	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	High
Properties of high yielding species	Water demand	• Match choice of planting material to site conditions	• Evaluate water-use efficiency of high-yielding stock	Medium
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	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	
Tying up 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		
Land ownership	Fragmentation	• Land-owner cooperatives		
Non-technical	Information and training	• One-stop shop for information and advice		

Challenge	Specific issue	Existing potential solution (needs to be re-examined for bioenergy production)	Innovative solution	Potential impact on cost of production
Non-technical	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		
Non-technical	Contract growing	• Contracts between grower and end-user with staged payments.		

6 Annual crops and crop residues

6.1 Description of the resource

Crop residues that arise on farms mainly comprise above-ground plant parts that are not the main product of the crop. These residues include leaves (e.g. sugar beet tops), stems (e.g. straw, which includes leaves and stems), and 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, usually off the farm, are not considered here. These can include waste from cereal processing and rejected potato tubers.

Crop residues arising in fields may be collected for uses such as animal bedding, mushroom cultivation, insulating materials, paper manufacture, and energy generation (Baral & Malins, 2014). Alternatively, crop residues may remain in the field where they have some value by supplying nutrients, reducing soil erosion risk, and contributing to soil organic matter (Baral & Malins, 2014).

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

- Cereals (including wheat, barley, oats)
- Oilseed rape
- Potatoes (main crop potatoes generally have the haulm 'destroyed', or desiccated, at least two weeks before harvest, by flailing and/or application of an agrochemical)
- A variety of field vegetable crops (including brassicas for example)
- Sugar beet
- Legumes (peas and field beans, of which field beans have the largest area)

The list above is based on crops having a significant UK area (greater than 100,000 ha) using data from (DEFRA, 2018). Of these crops, only cereals have residues that are often collected: cereal straw may be baled and removed or may be chopped and incorporated by the next cultivations.

Table 6-1 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%).

Table 6-1: Estimates of crop residue quantities arising in the UK

Crop	Area ('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 (DEFRA, 2018) and harvest indices from various sources as indicated below
(1) (AHDB, 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.

These estimates of quantities do not indicate availability for bioenergy production. For straw residues from cereals, that have significant current uses, availability for bioenergy feedstock depends on factors including demand for other uses (locally and for export to other regions), and the use for soil incorporation (see section 6.5). (Rozakis, et al., 2013) provide an example of an assessment for Poland, of straw availability for bioenergy, taking account of actual production, local use (including incorporation for soil conditioning) and the possibility of redistribution to regions with a deficit of straw. (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 (AD)), leaving 29% ‘unused’, presumably incorporated into the soil. More recent data are lacking, but stakeholder consultation indicated that use for bioenergy has increased, but 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 this incorporated straw to bioenergy. A survey made in 2012 (Townsend, et al., 2018) showed that 28.5% of straw 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 collection.

For oilseed rape and field bean residues, most is incorporated, but we have not found estimates for usage off the field.

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.

Field vegetables in the UK have an area of 117,000 ha (DEFRA, 2018) across a diverse range of crop species, and residues are generally either incorporated, or grazed in the field.

Orchard fruit in the UK has an area of 24,000 ha. A report of residue yields (at zero moisture content) from Italy gives values of 1.1 t/ha/y for prunings, and 1.8 t/ha/y from removed trees at the end of the orchard life (Boschiero, et al., 2015; Boschiero, et al., 2016). This would suggest a UK resource size of 69,700 t and an energy yield of 1,322 TJ. We have not found data for the fates of orchard prunings in the UK, but generally these are removed from the orchard.

Also included in this report section is an estimate of arboricultural arisings or residues. Arboricultural arisings consist of the residues produced from maintenance of domestic and municipal gardens, parks and of road, rail, canal and other transport corridors. Arisings in the UK have been estimated at 2.7 Mt (at zero moisture content) giving an energy yield of 51,300 TJ (based on a calorific value of 19 GJ/t). This resource is not well characterised in terms of geographic distribution, and it is assumed to be dispersed across the UK, with an unquantified portion of the resource in locations that have poor access for collection and removal.

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 cereal crop such as 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 to 92% of the level achieved 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 poor evidence for the potential of this concept in the UK.

The potential area of land that could be used for catch crops, whilst minimising the decrease in production of main crops, has not been assessed in this project. In principal this 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), with some insight 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. However, to give some indication of the potential, in the UK maize was grown on 221,000 ha in 2018 (DEFRA, 2019a).

To give an indication of the potential yield by early April, when a catch crop would be harvested to allow maize establishment, winter wheat 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, 2018). Furthermore, it must be assumed that not all of the above-ground biomass in April can 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.

6.2 Supply chain steps

Crop residues arise following a sequence of steps in the supply chain for the main crop product (e.g. wheat grain). These steps include plant breeding, land preparation, sowing, crop husbandry, and harvesting. The provision of feedstock from crop residues requires only one process step on the farm, which is harvest or collection, since the other process steps associated with crop production will occur for other reasons.

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.

In the case of orchard residues, the main additional supply chain step apart from normal orchard development and management is gathering of the material and storage of the material on or off orchard.

For catch crops, the supply chain steps are as for other crops such as miscanthus (see Table 2-2) although harvesting will only occur once.

6.3 Costs of feedstock provision

Costs of providing feedstock from crop residues, that are additional to the costs of crop production, are principally the costs of collection (**Table 6-2**). The yields used to calculate these costs (from **Table 6-1**) 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 6-2**.

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 or orchard residues.

Table 6-2: Costs of collecting crop residues, based on residue yields from Table 6-1

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).

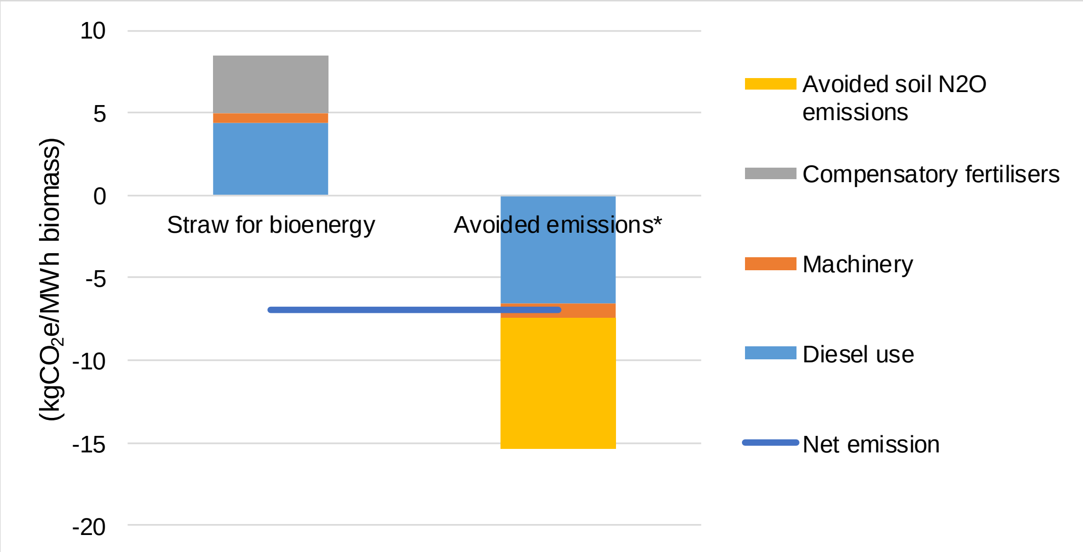
6.4 GHG emissions from production

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 other bioenergy feedstocks (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 6-1) 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.

GHG emissions from the supply of other crop residues or orchard residues have not been estimated but are expected to be low as only emissions from collection of the residue and any counterfactual need to be taken into account. GHG emissions from catch crops have not been estimated due to a lack of information on how the system would be implemented in the UK, but as they include the cultivation and harvesting of the crop could be higher.

Figure 6-1 GHG emissions from collection of straw



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

6.5 Other environmental impacts and benefits

Removing crop residues from a field can lead to loss of soil organic matter, soil carbon and available nutrients, and increase erosion (Scarlat, et al., 2010), compared with management that incorporates crop residues into the soil. The same authors reported that the effect of crop residue removal depends on crop species, farming practices (rotation, cultivations, fertilisation), site conditions (e.g. soil type, soil fertility, soil organic matter, risk of erosion, etc.) climate, and harvesting equipment.

(Nicholson, et al., 2014) estimated that straw incorporation leads to an average annual rate of soil organic carbon increase, of 330 kg of carbon per ha, which represents 0.36% of the C content of a typical arable soil in England. This estimate was based on an average straw application rate of 7.5 t/ha from experimental studies, which is high relative to typical commercial yields of removable straw (i.e. the straw that might be incorporated rather than removed, see Table 6-1). There was also much variation around this estimate, likely to be caused by variation in soil type, climate, weather, and management.

Consultation with stakeholders indicates that there are environmental impacts of collection operations: greater diesel use, soil compaction from baling and collection, greater need for cultivations to deal with soil compaction, and potentially yield impacts associated with later crop establishment.

Our consultation with stakeholders has identified a benefit of crop residue removal in some situations. Benefits for the environment can occur when removal of residues decreases pest and/or disease pressure, potentially decreasing the need for pesticide applications. It is not a usual practice to remove residues for this purpose, so the consequent environmental benefits are hypothetical.

6.6 Current challenges and barriers to production

6.6.1 Challenges and barriers

6.6.1.1 Quantity of supply

Although data on straw yields and uses are not available annually, and there is large annual fluctuation, there are resources available that are not currently used for purposes other than soil incorporation. The data in **Table 6-1** show that, for the main combinable crops, the UK production is over 11 Mt, of which over 3 Mt could be used for bioenergy feedstock, in addition to current use.

To give context to this quantity, there are approximately 1,767 kt of cereal straw that could be used for additional bioenergy feedstock (sum of values for wheat, barley and oats in **Table 6-1**, expressed as dry matter assuming 20% moisture), compared with 92 kt (mid-range estimate) of miscanthus produced in the UK in 2017 (DEFRA, 2019). This indicates that there is a viable quantity of additional straw that could be used for bioenergy.

6.6.1.2 Quality of potential feedstocks

(Shinners, et al., 2011) state that any material over 20% moisture content, and that needs to be stored, must be preserved by use of additives or by ensiling. This is relevant to residues that could be used in AD plants, from sugar beet, potatoes and horticultural field vegetable crops.

Crop residues have a higher ash content (the non-combustible inorganic content in fuels) compared with wood (Peng, 2018), and this higher ash content decreases the heating value.

Orchard residues (prunings) have variable quality depending on the species and the production practices; for example, pear or vine prunings were of lower quality than olive or hazelnut (Picchi, et al., 2018). This variation in quality affects combustion characteristics, but generally is within the range observed for forest residues (Picchi, et al., 2018). Orchard residues are green, small diameter, include leaf material, have very variable quality, and need tough equipment to produce chips; furthermore, a larger, wider-spectrum biomass boiler is needed to burn this type of resource (stakeholder consultation). By comparison, willow from coppice is more uniform in size and quality.

Consultation with stakeholders has raised the issue of soil contamination, particularly for sugar beet tops, and that this is a barrier to use in AD plants. Beet tops and leaves are difficult to pick up without soil contamination, have high water content (up to 90%), decompose quickly and have low energy content.

Oilseed rape has higher calorific value than cereal straw and can burn too hot, therefore it is used as a supplementary fuel only (stakeholder consultation).

Catch crops produce wet material suitable for AD feedstock.

6.6.1.3 Compatibility with other operations on farm

Consultation with stakeholders has confirmed that the major factor affecting the potential for straw to be diverted from chopping and soil incorporation to bioenergy feedstock supply, is the inconvenience to farmers associated with baling and removal of straw. Chopping and incorporation gives farmers control over the field operations leading up to drilling of the next crop; baling and removal often involves other parties, either contractors or purchasers. Furthermore, removal of straw can lead to soil damage through compaction, as heavy trailers traffic the land, and this can make cultivations and drilling more difficult. A further concern for farmers is the risk of bringing blackgrass seed onto the land through the equipment used for baling and removal of straw, and this risk is avoided by chopping and soil incorporation. For these reasons, a stakeholder indicated that many farmers would not part with residues even if a good price was offered; but another stakeholder claimed that farmers would sell straw if the price were sufficiently attractive.

6.6.1.4 Lost nutrient supply

Crop residues contain nutrients and therefore removal decreases the nutrient supply to following crops, and for optimal production the nutrients must be replaced by application of fertilisers. Consultation with stakeholders indicated that the nutrient content of straw was low, and that nutrient content alone is not a valid reason to incorporate straw into soil rather than baling and removal. However, it has been claimed that straw incorporation returns valuable nutrients to the soil, particularly P and K, leading to potential economic savings through reduced additions of organic and inorganic fertilisers (Nicholson, et al., 2014). This latter report provides collated data on the nutrient supply from different types of straw (**Table 6-3**).

Table 6-3. Nutrient content of straw based on average straw yields (from (Nicholson, et al., 2014)).

Crop	Straw yield (t/ha)	Phosphate (kg/ha)	Potash (kg/ha)	Magnesium (kg/ha)
Winter wheat	3.4	4.1	32.3	4.4
Spring wheat	3.4	5.1	42.5	4.1
Winter barley	2.8	3.4	26.6	3.6
Spring barley	2.5	3.8	31.3	3.0
Oats	3.0	4.8	50.1	6.6
Oilseed rape	1.8	4.0	23.4	ND

ND = no data.

Survey work has shown that nutrient benefits is among reasons that farmers give for not removing straw (Glithero, et al., 2013). If residues are removed for AD, organic matter may be returned, but often it is not returned to the same place, and farmers still feel that they are losing the benefit of residue incorporation (Stakeholder, 2019) - stakeholder consultation).

6.6.1.5 Soil structure issues

Consideration of the potential feedstock supply from crop residues should be based on the minimum level of crop residue that must be kept on land to maintain the soil quality, soil organic matter and reduce the risk of erosion (Scarlat, et al., 2010).

6.6.1.6 Farmer views/attitudes

Glithero et al. (2013) reported that timeliness of crop establishment and benefits of nutrient retention from straw incorporation were given by farmers as reasons for straw incorporation rather than baling and removal for another use.

Townsend et al. (2018) reported that 28.5% of straw chopped and incorporated would not be sold even if payments were generous; and 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 collection.

Despite the evidence from surveys, it was claimed in our consultation with stakeholders that there is anecdotal evidence that farmers would sell straw if the marketing and financial returns were good enough, even though they may put forward a different view when they respond to surveys.

Stakeholders viewed the ‘hassle factor’ as the biggest barrier for to bale and sell straw. Other barriers such as potential gain in soil organic matter and nutrient returns to the soil are of lesser importance to farmers. A farmer can chop the straw (using 9 L more diesel per ha), and then there are no further complications after harvest, such as blackgrass arriving on the field on contractors’ equipment, soil compaction from baling and transport, and delayed drilling of the next crop.

However, a stakeholder also took the view that return of residues to the soil is useful on very light land, such as sandy soils in north Norfolk where there is a need to improve moisture retention; and on heavy clay, where it improves workability. On other soils, the value as a soil conditioner is less and inferior to many other soil amendments like AD digestate, compost or used livestock straw/manure.
Climate and weather

A study comparing straw use in Denmark and Sweden (Bentsen, et al., 2018) suggested that there is an advantage for the supply of straw for bioenergy feedstock in regions where the weather is on average more favourable (warmer, drier) at harvest. This suggests that the climate in the west and north of the UK may be a barrier to the supply of straw for bioenergy feedstock, compared with central and eastern England.

6.6.1.7 Geographic distribution

Crop production is widely dispersed across the UK, which presents a logistical challenge for collection and transport from some locations. In areas where a large proportion of straw has been chopped and incorporated, such as parts of the south-east of England, the storage capacity has declined and is now a barrier to baling and storage ((Stakeholder, 2019) - stakeholder consultation). This reduces the available supply from some areas.

6.7 Responses to and impacts of challenges and barriers

In a study presented in a master's thesis, Sontag (2017) showed that market dynamics and farmer behaviour both are important influencers of straw availability for renewable energy production and drive annual variation in available feedstock. Furthermore, this modelling study showed that high rates of straw diversion from soil incorporation to bioenergy feedstocks can risk the sustainability of using straw for renewable energy production and lead to decreases in availability in future years, as a reaction to the negative effects on soil properties.

The barrier of nutrient loss when removing crop residues from the field can be overcome by return of nutrients to the field after combustion – e.g. fibrophos from poultry litter combustion (stakeholder consultation).

6.8 Supply chain innovations

The principle innovation for increased supply of bioenergy feedstock from crop residues is:

1. The use of 'dry' crop residues (e.g. straw, but excluding 'wet' residues that are not suitable for combustion) that are not currently collected from fields.

   We have named this as an innovation because it is the largest opportunity to increase bioenergy feedstock supply from crop residues; however, collection of straw (cereal and oilseed rape straw is the largest the largest potential resource among crop residues) from fields is not technically innovative, since this has been done for many years and the techniques and equipment are well developed. Furthermore, the incorporation of crop residues into 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 not necessarily unused, with the possible exception of orchard prunings, which are removed from orchards for disposal.

Other potential innovations that have been identified are:

2. Catch crop production for AD feedstock. For example, following cereal crop harvest in August or September, a cereal crop such as triticale could be sown in September and harvested as whole-crop for silage the following spring, before a late-sown crop such as forage maize is established.
3. Mapping to overlay power stations and production areas has been demonstrated and can encourage efficient straw collection and transport.
4. Spent straw for used for wintering carrots: around 405,000 t is available in England (little or none in Devolved Administrations). Around 100 t /ha of straw is used on carrot fields. Spent straw after carrot harvest is partly degraded, and suited to processing by steam explosion, allowing extraction of higher-value components, with the remainder used for combustion.
5. Innovation in the design of contracts can 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.
6. 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. Furthermore, compaction and/or dewatering would facilitate handling and transport.

Other innovations below are included for information but are out of scope because they are post-farm-gate.

- 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 cost of 30% to 66% depending on the treatment combinations. This is a post-farm innovation, so is out of scope, but is included here for information.
- Biomass torrefaction can be used to densify and stabilise feedstocks, encouraging greater use and therefore more collection.
- For straw there is scope for innovation at the combustion stage, and this could encourage greater feedstock supply.

7 Key findings

7.1 Energy Crops

Areas of perennial energy crops (*Miscanthus* and SRC Willow) in the UK are still low, despite previous policy support from the Energy crop planting scheme and support for use of bioenergy under renewable energy policy. Currently only 10,000 ha are grown (DEFRA, 2019).

The levelized cost of production (to the farm gate) (assuming a 5% discount rate) is estimated to be about £2.6/GJ (about £50/odt) (for typical costs, although depending on the site this can range substantially from about £2/GJ to £2.9/GJ for willow to £3.9/GJ for *Miscanthus* (Table 7-1). Costs are increased substantially for SRC if producers are required to pay land rent, although the impact on production costs for *Miscanthus* are les. A requirement for higher rates of return (10%) would also increase the price at the farm gate – to £3.1/GJ for SRC and £3.3for *Miscanthus* (assuming no land rent).

For both SRC and *Miscanthus*, harvesting accounts for about half of the overall production cost dur to the recurrent nature of the cost. The other major contributor to costs is planting material and planting, which accounts for just under a third of costs for *Miscanthus*, and about a quarter of costs for SRC. Changes in the costs of these two factors therefore have a significant impact on production costs, but the main factor to which the production cost is sensitive is (unsurprisingly) the yield that is achieved. This suggests that technical innovations which lead to an increase in yield (or potential yields being reliably achieved in the field), or a reduction in harvesting costs, or a reduction in the costs of planting materials and planting are likely to reduce production costs, improve profitability and potentially increase up take.

Table 7-1 Summary of levelised cost of production for energy crops

	Cost assumptions	No land rent (5% discount rate) £/GJ	Including land rent (5% discount rate)* £/GJ	No land rent (10% discount rate) £/GJ
SRC willow	Low	2.1		2.6
	Medium	2.6	3.8 (3.0 – 4.7)	3.1
	High	2.9		3.6
Miscanthus	Low	2.0		2.5
	Medium	2.6	3.8 (2.9 – 5.6)	3.3
	High	3.9		4.8

* Based on average land rent; range reflects costs assuming low and high land rents

The harvesting stage is also the main contribution to GHG emissions for SRC, mainly from emissions from diesel used for harvesting, but also the carbon footprint of machinery used for harvesting. This partly reflects the low level of inputs assumed for SRC. In the case of *Miscanthus*, while harvesting emissions are of the same magnitude as for SRC, emissions due to use of nitrogen fertilisers to maintain the crop are more significant.

Stakeholder consultation suggested a wide range of non-technical barriers still exists for energy crops, and that these will need to be addressed in parallel with addressing technical challenges if the industry is to develop. Furthermore, stakeholders pointed out that consideration and involvement of the whole supply chain would be necessary if production of energy crops is to take off – technology or supply push needs to be accompanied by market pull. Stakeholders also pointed out that large scale investment would be required at every step of the supply chain if energy crop production is to be expanded rapidly and significantly.

The review of the Swedish experience in SRC willow (Appendix A), suggested that the main focus of any program should be on the farmer´s profitability. It points out that a focus on optimization of biological productivity or maximising the environmental benefits from SRC could fail to optimize farmers profit, and hence reduce the farmers incentives to establish and grow SRC willow. It suggests that the ecosystem services from SRCw, which have been found to be substantial and diverse, should be recognized, but as they do not necessarily help with the profitability of SRC, may not be enough of a lever to encourage uptake. Incentivizing SRC (e.g. on the grounds of the societal benefits or public goods that the environmental benefits that SRC can provide) could be useful but the design of any scheme needs to be carefully considered. The Swedish experience suggests that it should be designed to promote high yields rather than just planting of large areas. This is because a focus solely on increasing the area planted, could result in SRC being established on small, remote and infertile sites inevitably resulting in low yields and high production costs, which could reduce farmer confidence in growing SRC.

The literature and stakeholders provided a wide range of potential innovations to address the barriers identified in growing energy crops. The innovations identified were focused on:

- Increasing yield and resilience in new varieties.
- Scaling up production of planting materials.
- Planting machinery innovations to increase establishment success and productivity.
- Increased establishment success and expansion of planting window.
- Development of new pesticides.
- Innovations in harvesting machinery to improve efficiency and access to difficult sites.
- Increasing knowledge on optimal harvesting.
- Feedstock storage innovation to ensure feedstock quality.
- Monitoring to improve yield and reduce costs.
- Alleviating concerns over difficulties with crop removal.
- Alternative end-uses to diversify markets and improve economics.
- Land use innovation to enable growers to benefit from multifunctional benefits of energy crops.
- Updated guidance for growers.
- Supply of robust, independent Information and advice.
- Lack of awareness in key stakeholder groups and public.
- Economic innovations.

Not all of these innovations fall within the remit of the innovation programme which is being considered and screening of the innovations will be needed at the beginning of the next task in the study to identify those which should be studied further.

The status of each of the innovations varies considerably, but generally it should be remembered that the energy crops industry is relatively young and immature, and while development work is underway for some innovations, the status of others is unclear.

7.2 Forestry

Long rotation forestry (LRF) is a well-established, mature industry, although it is typically focused on maximising production of the most valuable product, saw logs, rather than material suitable for use in bioenergy. Material for bioenergy, from early and pre-commercial thinnings, and as residues from the final harvest is typically considered as a by-product and currently efforts are often not made to maximise utilisation of it. Experience from other countries where bioenergy markets are more established does however suggest that the existence of a market can lead to forests being better managed, as thinning activities can generate extra income. The close connection between production for bioenergy and production of more traditional and valuable products in LRF (i.e. saw logs) means that innovations have been considered that focus on the whole forestry production system, not just production of material for bioenergy.

In the case of short rotation forestry, while a number of trials were established in 2010 to 2013 at sites round the UK, there has not been extensive uptake of this approach and as the trials have not yet matured, a robust evaluation is difficult. Cost data estimated by Forest Research for this study suggests that production costs, including chipping at the forest site could be £6.8/GJ for broadleaf SRF and £9.3/GJ for coniferous SRF (assuming a discount rate of 5% and excluding land rent), although costs could vary significantly by site Table 7-2). If the SRF was being grown on low grade agricultural land and land rent was payable, then this could increase the cost of producing the woodchip by about 20%. As with energy crops, harvesting is the most significant contribution towards production costs accounting for just over half of costs where not land rent is payable, with planting costs accounting for about a fifth. As with energy crops, costs per GJ are inversely proportional to yield so are sensitive to this; as trials have not yet completed, there is some uncertainty over the yield which will be achieved at the end of a 15 year period, and the typical yields assumed in the cost calculation are based on an extrapolation of growth rates achieved to data. .

The estimates suggest that the cost of producing SRF is significantly higher than energy crops; While they include chipping which is not included in energy crops harvesting costs, this only accounts for about 20% of SRF production costs. So, even allowing for this difference, SRF production is likely to be more expensive than perennial energy crops, unless yields higher than those assumed for the costs estimate (80 odt/ha for conifers and 120 odt/ha for broadleaf).

Table 7-2 Summary of levelized cost of production for SRF

	Cost assumptions	No land rent (5% discount rate) £/GJ	Including land rent (5% discount rate)* £/GJ	No land rent (10% discount rate) £/GJ	Including land rent (5% discount rate)* £/GJ
Conifer	Low	5.9	5.9	8.0	8.0
	Medium	9.3	11.5	13.0	16.6
	High	13.5	16.5	19.2	24.2
Broadleaf	Low	4.8	4.8	6.9	6.9
	Medium	6.8	8.3	9.5	11.9
	High	10.0	12.0	14.3	17.5

* Assumes no land rent for low case, minimum land rent of £131/ha for medium case and average land rent of £181/ha for high case)

A number of the technical innovations identified are applicable to both LRF and SRF

- Species selection
- Provenance choice
- Genetic improvement

- Mixed species stands
- Soil preparation by ripping
- Direct seeding
- Changing initial spacing between trees
- Fertilising crops using anaerobic digestate Innovations for forestry
- Harvesting technology

Others are applicable to only LRF

- Remote sensing for crop monitoring and management
- Manipulating cut-off diameter
- Removal of stump to ground level
- Residue removal
- Stump and root removal

In addition, agro-forestry combining trees with poultry or grazing animals, or trees with other crops could offer a variation on current supply chains.

Most of the innovations aims to reduce costs and improve the profitability of the forest system. As the forestry industry is well established, assessment of the status of the innovations, key players, and the potential impact on costs is likely to be easier than for energy crops.

As with energy crops, stakeholders identified a number of non-technical barriers, and the non-technical innovations which could address these.

7.3 Crop Residues

The largest opportunity to increase bioenergy feedstock supply from crop residues is the use of resources that are not currently collected from fields. However, collection of straw (cereal and oilseed rape straw is the largest the largest potential resource among crop residues) from fields is not technically innovative, since this has been done for many years and the techniques and equipment are well developed.

For the main combinable crops, the UK production of crop residues is over 11 Mt, of which over 3 Mt could be used for bioenergy feedstock, in addition to current use for bioenergy feedstock. Drier crop residues (under 20% moisture content) could be used for combustion and ‘wet’, green residues (which have a variable moisture content but are usually greater than 50%) can potentially be used for AD.

However almost all field residues from major crops in the UK are already used, either for soil incorporation, or by removal from the field for other uses such as livestock feed or bedding. There is also evidence that some farmers would be unwilling to sell residues for bioenergy because of the value they place on use of residues for soil maintenance and improvement.

In the case of straw, which is the main crop residue currently used for bioenergy, innovation in the design of contracts can 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. Mapping to overlay production areas and power stations combusting straw has been demonstrated and can encourage efficient straw collection and transport.

A potential residue which does not currently have an end use and could be utilised for bioenergy is orchard residues, Orchard fruit in the UK has an area of 24,000 ha, and it is estimated this generates 69,700 t of prunings and end-of-life residues, with an energy content of 1,322 TJ. Since orchards are mainly grouped in areas such as Kent, Somerset and West Midlands, collection of orchard residues for combustion may be practicable.

Catch crop production for AD feedstock is a possible innovation that could make better use of land. However, there are data gaps for the potential area and for the potential yield under UK conditions.

Glossary

(B)VOC	(Biogenic) Volatile organic compound
(D)EC	(Dedicated) Energy Crops
(D)EC	(Dedicated) Energy Crops
AD	Anaerobic digestion
BPS	Basic Payment Scheme
C	Carbon
CCF	Continuous Cover Forestry
CEO	Chief Executive Officer
CoF	Characterisation of Feedstocks (ETI project)
Dbh	Diameter at breast height
DTI	Department of Trade and Industry
EAMU	Extensions of Authorisation for Minor Use
ENGO	Environmental Non-Governmental Organization
ETI	Energy Technologies Institute
EWGS	English Woodland Grant Scheme
FC	Forestry Commission
FLS	Forestry and Land Scotland
FR	Forest Research
FS	Forest Service (Northern Ireland)
GB	Great Britain
GE	Genetic engineering
GHG	Greenhouse gas
GM	Genetic modification
GWh	GigaWatt hour
ha	hectare
LiDAR	Light Direction and Ranging
LRF	Long Rotation Forestry (conventional forestry)
NC	Natural capital
NGO	Non-Governmental Organization
NGO	Non-governmental organisation
NRW	Natural Resources Wales
NSA	Nitrate Sensitive Area
odt	Oven dry tonne
Odt	Oven dried tonne
PR	Public Relations
QA	Quality Assurance
RELB	Refining Estimates of Land Biomass (ETI project)
RHI	Renewable Heat Incentive
SE	South East
sph	Stems per hectare
SRC	Short rotation coppice (w = willow, p = poplar)
SRC(p)	Short rotation coppice (poplar)
SRC(w)	Short rotation coppice (willow)
SRF	Short Rotation Forestry
SSSI	Site of special scientific interest
SW	South West
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UKFS	UK Forestry Standard
USA	United States of America
WoS	Web of Science

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Appendices

Appendix 1: Review of short rotation coppice in Sweden

Appendix 2: Organisations consulted

Appendix 1

A.1 Review of short rotation coppice in Sweden

A.1 Review of short rotation coppice in Sweden

A.1.1 Overview of Swedish SRC supply chain

A.1.1.1 Market emergence 1960-1996

The starting point of the Swedish short rotation coppice (SRC) system was actually not an ambition to produce biomass for energy, but rather to increase the supply of pulpwood for the Swedish pulp industry. However, during the 1970´s, a substantial political momentum was created by the oil crises resulting in an ambition that Sweden should become more self-sufficient as regards energy. This led to a shift of focus from pulpwood to biomass for energy.

Massive investments were made in R&D on biomass for energy (mainly willow SRC) during 1975-1990 at the Swedish University of Agricultural Sciences financially supported by governmental bodies. This was combined with the establishment of a set of economic incentives for the Swedish energy and agricultural sector (Johansson et al., 2002; Ericsson et al., 2004). Taxes on CO_2 from fossil fuels for heat production as well as on energy were introduced in 1991, and were progressively increased from 0.02[15] GBP/kg CO_2 in 1991 to 0.03 GBP/kg CO_2 in 1996. These taxes on fossil fuels made biofuels competitive versus fossil fuels.

In addition, a domestic de-regulation of the Swedish agriculture starting in the late 1980´s included set-aside schemes with very significant subsidies for producing alternative crops or taking arable land permanently out of production. During the period 1991–1996, a subsidy of 769 GBP/ha was paid to farmers who took a part of their crop land out of production, and in addition, a specific subsidy of 855 GBP/ha was available for planting of SRC willow (Johansson et al., 2002).

For long, Sweden has had a system with district heating plants providing district heating in all larger communities. When energy and CO_2 taxes were introduced, these district heating plants were converted so that they could be fueled with biomass (mainly from the huge Swedish forest sector but also from peat), and power generation was typically introduced (combined heat and power; CHP). This led to a rapid increase in the demand of biomass for energy (Junginger et al., 2005). The consumption of tree-based fuels for district heating and CHP in Sweden increased from approximately 5 TWh in 1990 to approx. 18 TWh in 1996 (Swedish Energy Agency, 2019a). As shown by Rosenqvist et al. (2000), a nearby district heating plant, with an increasing demand of biofuels, raises the confidence of the farmers in SRC willow as a viable crop.

Thus, for some years during 1990-1996, there was a simultaneous pull and push effect resulting in a rapid development of the Swedish SRC system (Mola-Yudego and Pelkonen, 2011). The area of SRC grew from approximately 1,000 ha to around 14,000 ha during this period (Fig. 1; Agrobränsle AB, unpublished data) generating a small but significant market for plant material, machinery and the woodfuel produced at harvest.

A.1.1.2 Market maturing 1997-2007

In 1995, Sweden entered the European Union, and in 1996, the CAP was introduced in Sweden. The planting subsidy was initially reduced to a third of its previous amount (i.e. 294 GBP/ha 1997-98¸ Lindegaard et al., 2016), and the number of new plantations dropped significantly, i.e. from 2170 ha in 1996 to 84 ha in 1997(Agrobränsle AB, unpublished data). By that time, most of the Swedish plantations had also been harvested for the first time. In contrast to the anticipated productivity of up to 12 tonnes of dry matter (DM) per ha and year, the actual harvest figures after the first rotation (i.e. time between harvest) equaled 2.6 tonnes DM/ha yr (Mola-Yudego and Aronsson, 2008). This "yield gap" was specifically addressed by Mitchell, Stevens and Watters(1999). Also Mola-Yudego et al. (2015) discussed the yield gap and suggested that a large proportion of headlines (i.e. edges and

[15] 1 GBP=11.7 SEK

borders not planted with SRC willows) as well as inappropriate management (weeding and fertilisation) were assumed to contribute to this yield gap.

New willow varieties were introduced on the market, and advisory service provided advice for better management of the plantations resulting in higher yields and less problems with pests and diseases. Development of new or improved machinery resulted in lower costs for planting and harvest. However, yield data only slowly increased and reached 4.2 tonnes DM/ha yr as an average for the second cutting cycle, and 4.5 tonnes DM/ha yr for the third cutting cycle (Mola-Yudego and Aronsson, 2008).

During the late 1990s, there was a shift towards a more market oriented situation with farmers establishing SRC based on conventional and realistic investment calculations. In addition, new and highly productive SRC varieties were introduced on the market partly changing the conditions for calculating revenues (Mola-Yudego, 2011).

A.1.1.3 Market decline 2008-2018

Unfortunately, but predictably, many farmers had chosen to establish SRC on remote sites and on small and unfertile fields (Dimitriou, Rosenqvist and Berndes, 2011). Low productivity in combination with high costs for transport of the harvested wood chips resulted in low revenue for the farmers. Many farmers obviously had not focused on the revenue from the SRC production but more on other aspects e.g. maximizing subsidies (Helby, Rosenqvist and Roos, 2006).

During the period 1997-2010, the area of SRC in Sweden was quite stable but then started to decrease from a maximum of approximately 14,000 ha down to less than 8,000 ha in 2017 (Agrobränsle AB, unpublished data; Swedish Board of Agriculture, 2017 – see Figure 1). This reduction can be connected to the fact that the first plantations established in the early 1990's had now reached the age of ca 25 years (an age limit that is commonly believed to be the upper limit of a productive SRC plantation). Most of the farmers remove the SRC willow plantation from their fields but they do not replace it again with new willows.

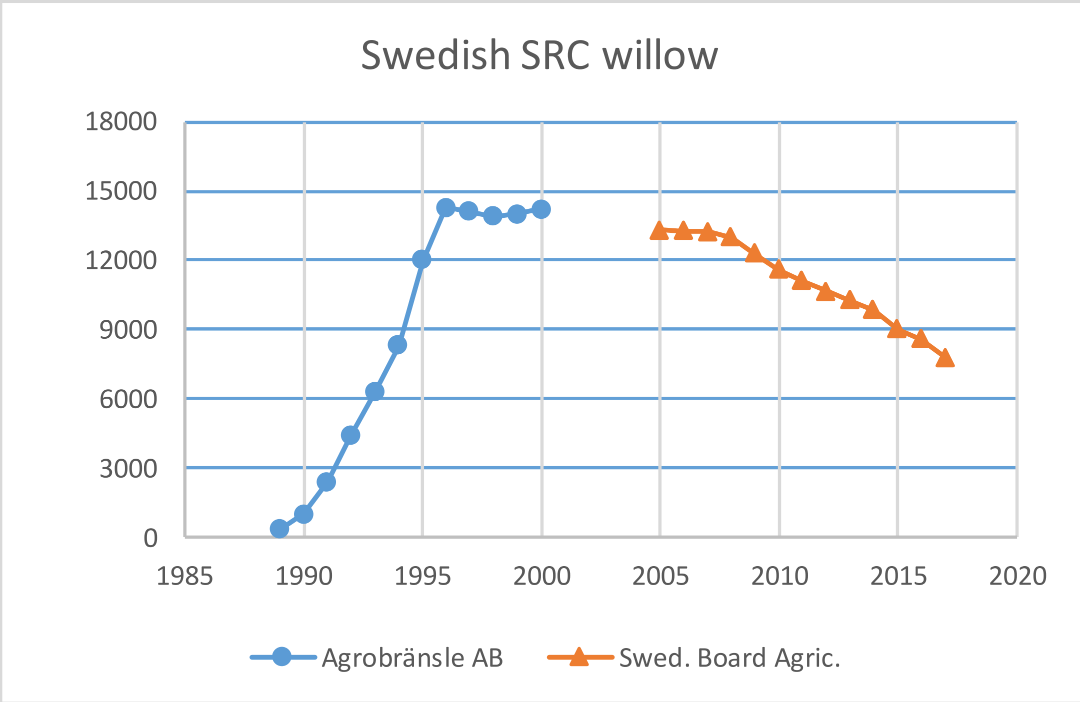
A thorough analysis of the development of the SRC market in Sweden during the 1990´s is provided by Helby et al. (2006).

A.1.2 The Swedish SRC market situation

During the early 1990´s, business models around SRC were developed. Initially, several local farmer cooperatives started up business around SRC wood chips and provided harvest operations. Soon, all operations were transferred to a new company, Agrobränsle AB, owned by the Swedish farmer´s cooperative (Lantmännen) and to a smaller part by the Swedish Farmers Association (LRF).

Agrobränsle developed a business model which included the entire chain from planting to harvest and selling the wood chip produced. It also included application of sewage sludge to the newly harvested SRC plantations as a means of providing fertilisation. The detailed economy in this is not known, but at that time Swedish wastewater treatment plants had significant problems finding use (or ways to dispose) of the sewage sludge. Farmers accepting application of sewage sludge after harvest were paid somewhat better by Agrobränsle, and it was widely assumed that Agrobränsle profited substantially from taking care of sewage sludge.

Figure 1: Swedish farmland (ha) used for growing SRC willow



Source: 1989-2000; unpublished data from Agrobränsle AB. 2005-2017; data from the Swedish Board of Agriculture

In 2002, Agrobränsle acquired the commercial willow breeding program from SvalövWeibull AB including the breeder´s right to the commercial varieties used in Sweden as well as in Poland and other European countries. By this Agrobränsle positioned itself as a full monopoly player in Sweden. In fact, the managing director commented on this in media stating that the company had a "Microsoft position" on the SRC market (Sydsvenskan, 2003). Agrobränsle charged royalty fees for the planting material corresponding to approximately 128 GBP/ha (Gustaf Melin pers. comm., 2003)[16]

Yields at harvest were still unexpectedly low, and the SRC farmers profit quite weak. The entrepreneurs running the planting and harvest operations on behalf of Agrobränsle complained about low remuneration for their work, while, at the same time, there was very little room for new players and new business models.

In 1996, a willow breeding programme was initiated at IACR-Long Ashton as a partnership between IACR-Long Ashton, Svalöf Weibull AB and Murray Carter ("the European Willow Breeding Program"; Lindegaard and Barker, 1996; Lindegaard, 2000). In 2002, the scientific part of the program was transferred to Rothamsted Research. The European Willow Breeding Program was eventually dissolved and breeding then continued separately in Sweden and in the UK (Karp et al., 2011).

As the market for SRC started to decline in Sweden, in 2010 the major part of Agrobränsle was sold to the company Salixenergi Europa AB run by two veteran entrepreneurs in the SRC sector. The commercial willow breeding program was transferred to another company in the Lantmännen corporate. A few other actors emerge on the market developing new willow clones and offering plant material and other plantation management services (e.g. European Willow Breeding, www.ewb.nu; Henriksson Salix AB, www.salixab.se). In all, this resulted in a new market situation with much more focus on profitability and testing of new supply chains and technologies.

[16] 1 GBP=11.7 SEK

A.1.3 Process steps

The SRC value chain includes the following parts:

- Production and sales of cuttings for planting
- Establishment
- Management
- Harvest and transport
- Heat and/or electricity production including distribution[17]
- End use of heat and/or electricity[18]
- Removing of plantation

A.1.3.1 Production and sales of cuttings for planting

Cuttings are produced in wintertime. Two commercial companies are producing willow cuttings. For the production, long rods but also short cuttings are produced from 1 year-old shoots. The cuttings are produced in an unbroken chill chain and stored at -4°C under constant monitoring so that germination can be guaranteed. Cuttings are then packed in cardboard boxes, and planting should be done within 10 days (Salixenergi Europa AB, 2019).

A.1.3.2 Establishment

The establishment phase includes site selection, soil preparation and planting. Site should be chosen considering soil requirement of the SRC, and prerequisites for efficient management and harvest. This implies large fields with long rows (Pacenka and Hoffmann, 2015). Establishment is usually made by planting 15-20 cm long willow cuttings. Planting takes place in early spring and should ideally start as early as possible. Early planting means better establishment and growth during the first year.

SRC willow is planted in a double-row system. The distance between the rows alternates at 75 and 150 cm to allow for the harvesting machines to harvest one double row at a time. The distance between double rows has changed over time as has the distance between the plants in the rows which has increased from 50 cm to 60-70 cm or even up to 90 cm (Mitchell, Stevens and Watters, 1999) resulting in an average plant number of 10,000-14,000 plants per ha. An alternative establishment technique with lay-flat shoots 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 (Dimitriou 2013; Lowthe-Thomas, Slater and Randerson, 2010; Mccracken at al. 2010). However, the lay-flat system requires more propagating material that adds to the costs plus costs related to royalties. Therefore, it has not yet been widely adopted although growth performance and survival rates were equally good or better than the conventional planting with horisontal cuttings.

A.1.3.3 Management

Management of SRC includes weeding, primarily the first year after planting, and fertilisation. Besides herbicides, no other pesticides are being applied. Different mechanical and chemical weeding strategies have been developed for different regions of Europe. The importance of weeding and effect of different weeding strategies on productivity has been studied e.g. by Albertsson et al. (2016).

Fertilisation of SRC is widely recommended (e.g. Lantmännen Agroenergi; Swedish Board of Agriculture, 2019), whereas the economic benefit of fertilising is highly dependent on costs for fertiliser and the marginal value of the increased production (Aronsson, Rosenqvist and Dimitriou, 2014).

[17] Not further discussed

[18] Not further discussed

A.1.3.4 Harvest and transport

A SRC crop is harvested every 3-5 years using one of the harvest system available on the market (i.e. direct chipping, billet harvest, baling system). In practice few alternatives are available in the different regions since the few actors involved and the high investment costs for harvest machinery has resulted in natural monopoly developed in many regions of Sweden.

Three harvesting systems predominate in Europe: direct chipping, whole shoot harvest, and bale harvester. In the UK a billet harvester has also been adopted chopping the shoots in longer stem pieces enabling long-term storage of the harvested biomass. The direct chipping method has by far the highest capacity, but also includes the most powerful (and fuel consuming) engines (Vanbeveren et al., 2017). The harvesters used in Sweden were originally corn-harvesters slightly modified to better suit harvest of SRC willow. The modified cutting heads were owned by Agrobränsle whereas the base machines were owned by entrepreneurs contracted by Agrobränsle. The entrepreneurs were not allowed to use the cutting heads for harvesting for other companies than Agrobränsle, which led to a significant frustration among the entrepreneurs especially since they commonly invested their time as well as money into further developing the cutting heads. After Agrobränsle AB was closed in 2012, further efforts to improve existing cutting heads and develop new harvesting techniques have been financed by private funding and in some cases with support of the Swedish Energy Agency.

Direct transport to district heating plants using large containers is the most common practice. Sometimes, pile storing on the field is chosen for logistical reasons. Long-term storage of chipped SRC is avoided due to substantial weight losses during storage. Billets (i.e. longer stem pieces) are much more suitable for long-term storage as are bales of shoots coming from the bale harvesting system.

At the district heating plant different wood fuels are mixed with other fuel types to achieve a suitable fuel mix as regards water content and combustions properties. Small district heating plants have been reluctant to buy SRC fuel since they typically have fewer options to mix fuels, and are afraid of combustion-related problems if temporarily using 100% SRC fuel. There was a general belief among district heating plants not using SRC fuel that it would cause sintering problems, whereas those district heating plants that did use SRC fuel reported few problems in this respect.

A.1.3.5 Removing a SRC willow plantation

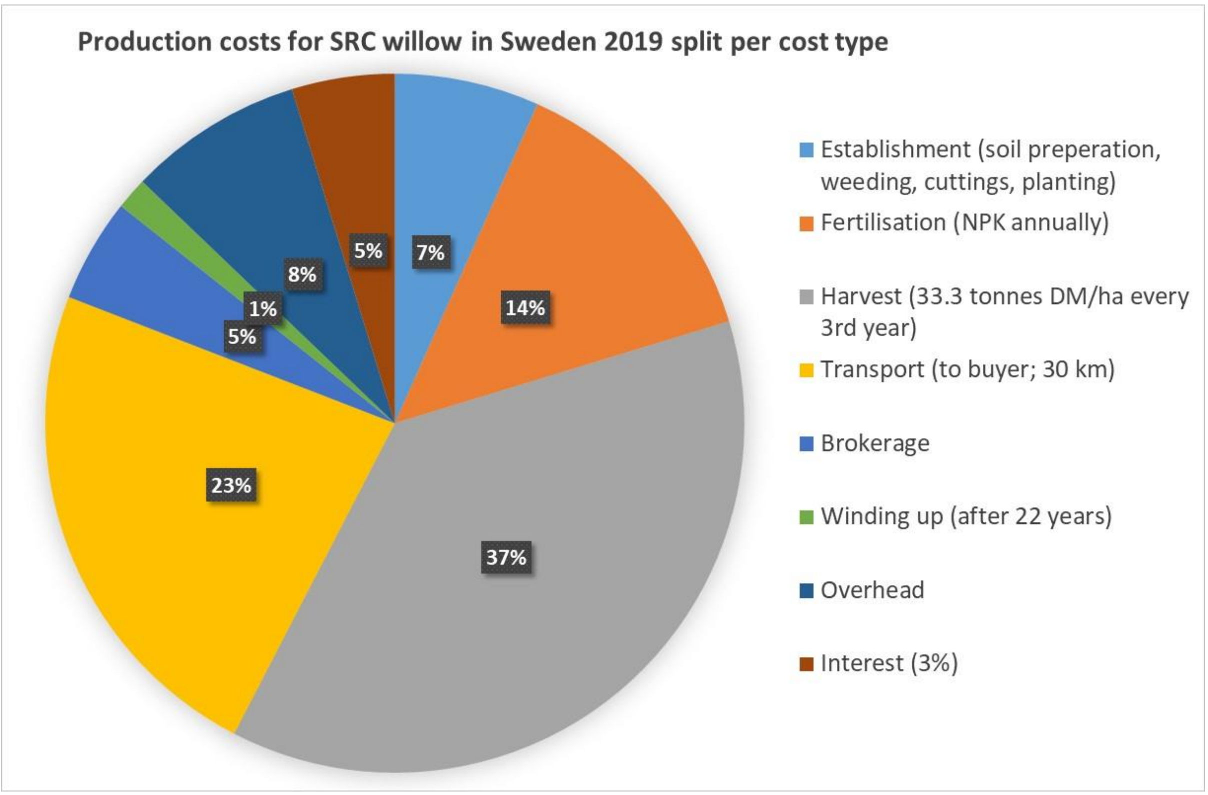
Removing of an SRC plantation was initially considered a problem or at least a factor of uncertainty among farmers as regards efforts required and costs for reclaiming the land. These concerns were not proved to be true and it is now widely acknowledged that following recommendations on how to succeed with removal guarantees a successful and reasonably inexpensive removal, that allows for either replanting of SRC or to continue with annual crops (Nordh, 2012).

A.1.4 Production costs for SRC

The costs for producing wood fuel from willow SRC in Sweden have for many years been studied by Rosenqvist and co-workers. There are different approaches to the issue of production costs e.g. as regards including or excluding costs for land and costs for risk. One can argue for including as well as excluding those costs. Here, production costs excluding costs for land and for risk are presented.

Figure 2 below presents production costs for willow SRC wood fuel as presented by the Swedish Board of Agriculture (Rosenqvist,unpublished data) Berndes and Börjesson (2013). A thorough description of economic calculations for European SRC is presented by Rosenqvist, Berndes and Börjesson (2013).

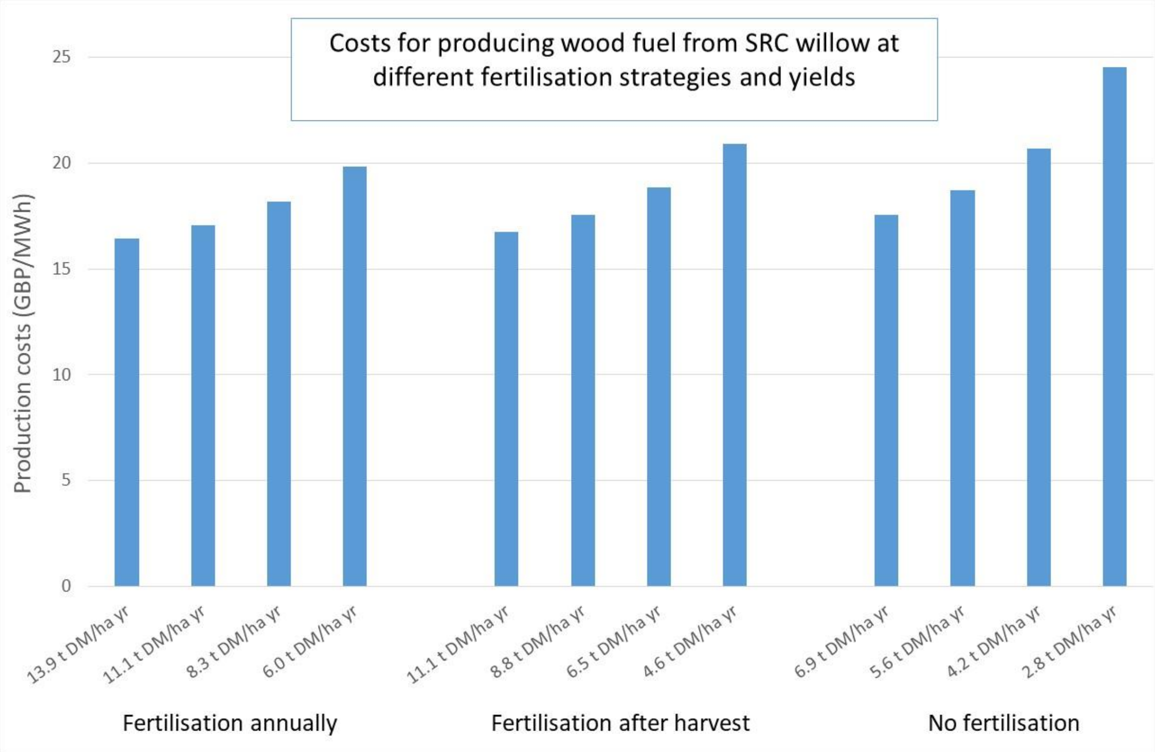
Figure 2: Production costs for Swedish SRC willow per 2019 as percentage per cost type.



Notes: Total production cost for this specific case is £18.1/MWh (£5/GJ). Costs do not include risk and opportunity costs for land. Costs depend heavily on yields, fertilization strategy

The production costs depend heavily on yield (negatively correlated), and costs for fuel and fertlisers (positively). The economic return on investing in fertilization depends on the yield response on fertilizing, and is not easily determined beforehand. In Figure 3, different cases as regards return on investment from fertilisation is presented.

Figure 3: Costs for producing wood fuel from SRC willow in Sweden 2019 under different fertilization strategies and yields.



Note: costs do not include risk and opportunity costs for land. Costs include the same types of costs as shown in Figure 2. Data from H. Rosenqvis

The profitability of SRC is in turn highly dependent on the income from selling the wood fuel produced. During 2014-2019, the price of wood fuel has varied between 14.9 and 16.9 GBP/MWh in Sweden (Swedish Energy Agency, 2019b). This points at the currently weak economy in growing SRC in Sweden in recent years. However, presently, without specific subsidies, no other dedicated energy crop intended for solid fuel production can economically compete with SRC willow in Sweden.

A.1.5 Factors that have helped to improve yields, costs and efficiency of production

A1.5.1 Actions taken for yield improvements

In the late 1970´s, by means of a competitions announced in a countryside magasine (Land), readers were challenged to send tall shoots of willow to the Swedish University of Agricultural Sciences (SLU) as a starting point for a national breeding program. After initial tests, these collected varieties were propagated and used in large-scale SRC plantations in the late 1980´s. In parallel, a commercial breeding program was initiated by the commercial plant breeding company SvalöfWeibull AB resulting in new varieties with significantly higher growth rates and resistance to plant pests. At the same time, the basic research on e.g. genetic variability and genetic markers were continued at SLU via a number of research projects funded by governmental bodies (mostly from the Swedish Energy Agency – a list with project names available if so wished).

A1.5.2 Actions taken for cost reduction

In terms of R&D much less efforts have been made to reduce costs as compared with increasing the understanding of biogeophysical parameters of SRC. One example was the study of an alternative technique for planting (described above). Efforts for cost reduction were mainly made by the commercial actors, i.e. Agrobränsle and its successor Salixenergi Europa. In parallel, several entrepreneurs made various innovations increasing the performance of the harvesters and thereby lowering the production costs. Initially (i.e. during the 1980´s), also technology for weeding was developed. This line of development was abandoned in the early 1990´s.

Results from the Swedish forest fuel sector show that the main cost reductions in harvest operations are due to learning-by-doing, improved equipment and changes in organisation (Junginger et al., 2005). There is no reason to believe that the Swedish SRC system would be different in this respect. However, there is a major difference as regards competition on the market. The forest biofuels sector includes several actors whereas in the Swedish SRC sector, in practice Agrobränsle AB and its successor Salixenergi Europa AB constituted the relevant actors on the market for more than two decades.

Around 2010, innovative technologies for harvest were tested in field and evaluated by researchers. Such technologies enabled storing of harvested SRC (billets and whole-shoot baler). This improves durability and speed when harvesting old SRC with very large shoot diameter. In Sweden, a substantial effort was also made to produce a bundler-harvester. This project has yet not been finalised.

As previously described, a very common practice was to use sewage sludge as fertiliser after harvest. This would add nitrogen (and phosphorus) to the SRC, but the main gain was the fee paid by the wastewater treatment plants for taking the sludge (Dimitriou and Aronsson, 2005; Paulrud et al 2016). As a means of bridging over the low interest among farmers for establishing SRC during the late 1990´s, the Swedish Energy Agency financially supported projects aiming at gaining multifunctionality in SRC. Recycling of sewage sludge was one such aspect, and recycling of both domestic and industrial wastewater as well as landfill leachate others. This resulted in improved goodwill for SRC among Swedish NGO:s as well as among local and regional administrative stakeholders. However, farmers were not particularly impressed or influenced by this effort.

A1.5.3 Actions taken for increased efficiency of production

In Sweden and the other countries with substantial area of SRC, numerous actions were made to increase efficiency of production. These includes several biological aspects on productivity:

- Plant breeding to achieve varieties with high productivity, tolerance to fungi (mainly leaf rust; Melampsora spp), frost, and with growth characteristics suitable for the current harvest system.
- Research on biological aspects on establishment such as storage of cuttings, cutting length, lay-flat planting, suitable timing of planting, and the effect of cut back of the plants after the first growing season.
- Research with fertilisation trials with N to test the fertilisation response of different varieties and produce N fertilisation guidelines.
- Research on efficient weeding strategies.
- Research on basic plant physiology in order to gain better understanding of nitrogen and water use efficiency and other traits targeted in the plant breeding.

In parallel to this research, technical development took place in close collaboration between the scientific community and the commercial actors resulting in guidelines and best management practice.

Besides these biological R&D, projects with focus on technology were also developed, mainly driven by the commercial actors in the sector and partly financially supported by governmental agencies (see above).

Within the SRC research, substantial efforts were made to find optimum solutions for bioenergy supply chains for different regions in Sweden. Such efforts typically included GIS-based analyses of the best locations for producing different biofuels. These studies were helpful to explain what already had happened in the SRC sector but had probably very little impact on the farmers planning and incentives for establishing SRC. Those research efforts are somewhat typical of the research focus in the Swedish SRC. For decades, there was a widespread idea that it was possible to optimise the Swedish bioenergy system if just authorities and farmers would realise where and how SRC best should be established and managed.

During the last 20 years, the Swedish Energy Agency has contributed with approximately 10.7 million GBP for R&D projects addressing the willow SRC supply chain and ecological and societal aspects on this crop (Swedish Energy Agency, 2019c). In recent years, several projects have focused e.g. on improved harvest technology such as modification/optimisation of one of the cutting heads used for direct chipping of SRC, a new system for bunchharvesting, use of conventional forest harvesters for handling very thick stems, SRC as raw material for production of wood pellets, improved billet harvester, and introducing a driving wheel on the biobaler harvester system. A list of technical R&D projects with governmental funding the last 10 years is presented below in Table 1.

A.1.6 Challenges

A1.6.1 Challenges for the Swedish SRC supply chain

The current situation in Sweden includes several challenges for increasing the area of SRC:

- Bad will due to too high expectations on yield and revenue, and from rumors about other farmer´s (bad) experiences with SRC during the first decade after introduction of willow SRC as a crop.
- The low productivity was in turn to a large extent a result of lack of focus on production among farmers and more on maximising subsidies. This resulted in establishment of SRC on remote, low-fertile sites with very low chance of profit from the production.
- Long-term commitment required for positive revenue (high establishment costs require several cutting cycles each 3-5 years long in order to reach break-even).
- Unpredictable cash flow due to fluctuating demand and prices for wood chips, and inability of the entrepreneurs to harvest due to weather conditions.
- Increased demand for farmland for annual crops and grass ley in recent years combined with increased prices for farmland has made SRC less competitive.
- Rather long periods of falling prices for solid biofuels, e.g. between 2011 and 2016, reduced the motivation to invest in SRC.
- Several district heating plants have reduced their demand for wet wood fuels in favor of fuels based on waste and imported residues (e.g. imported demolition wood).
- The harvest technology needs to be developed for enabling harvest during wet conditions and for enabling storing of harvested wood.

Table 1: Publicly funded R&D projects (since 2009) in Sweden addressing technical aspects of SRC

Project title	Project summary	Public funding
Development of UK planting machine for Swedish conditions	Planting the cuttings is an important step in the cultivation of salix. Within this project it is intended to develop a new technology that originally comes from England. The Swedish company Agrofuel has bought the rights to the technology and the hope is that it will significantly cheapen and rationalize the cultivation.	£65,726
Energy crops in a local loop - "Borås model"	Society is facing a growing challenge when it comes to close cycles and take care of waste and residues and produce nutrients without dependence on fossil fuels. Today we have relatively good skills about how to grow energy crops or dispose of the waste products, but we must develop bioenergy solutions and market models that are profitable. The overall objective of the project is to better understand how energy crops and waste products from agriculture can be part of a local cycle that provides a profitable production with the help of synergies from the sludge handling and bio-fertilizer.	£38,462
Conversion of the HSAB Billet Harvester to track drive	Henriksson Salix AB (HSAB) applies for funding for rebuilding the HSAB Billet Harvester to track drive. The HSAB Billet Harvester is a direct chipping self-propelled harvester which produces billets of three different lengths, 15, 20 or 30 cm. Billets is a storable fuel which dry during storage and which can also be used for planting to half the cost compared with conventional technology. The project is a continuation of the modification from cane to willow which was made during 2014-2015 with successful results. About 2500 m^3 of billets were supplied to some of heat plants in Skåne and 5 hectares was planted with billet planting in Lithuania. To get acceptable floatation during wet conditions the Billet Harvester needs to be equipped with track drive and contacts with various manufacturers of track units show that it is feasible. Widening the distance between the vertical feed rollers will also be made to improve the feeding of thick and crooked stems.	£68,120
Handling of cadmium at the heating plant with the use of willow as a catch crop	Environmental Protection Agency (EPA) got in the appropriation for the year 2013 the task to develop milestones for exposure to cadmium via food. The report points out directed cultivation of Salix, to remove cadmium from arable land as a measure. The measure would primarily concern the arable land with excessive levels of cadmium. The main use of willow today is as fuel mix with other biofuels in large power and heating plants. The combustion of willow grown on soils with high levels of cadmium, transform the problem with cadmium to the heating plant and the need to handle larger amounts of cadmium in an environmentally sound manner. The overall objective of the project is that through full-scale trial to demonstrate to the market the effect of high levels of cadmium in willow as a fuel for grate combustion with flue gas condensation and show the measures that can reduce environmental problems in the handling of ash and condensate.	£64,017

Project title	Project summary	Public funding
Billet harvester for salix	The project shall produce a prototype billet harvester for salix. The project is the result of a pre-feasibility study which showed that billets will dry over the summer without artificial drying from appr 50 % to appr 30% moisture content with maintained quality. The billet fuel is handled efficiently in bulk and fits the market for dry and storable fuel. The prototype for production of 30 cm and 10 cm billets will be developed using a standard billet harvester during 2014- 2015. The shorter billets can probably be used in some heat plants without further processing. The construction work will be done in 2014 and concerns the cutting, feeding and chopping mechanisms and incorporates experience from the construction of the HSAB salix head for SPFH. Field tests will be done in 2014 and 2015. Billets harvested in March 2015 will be stored over the summer, the moisture content and temperature will be measured, and test deliveries will be done to heat plants the coming fuel season.	£98,462
Improved fuel quality of willow chips through optimisation of harvest time	Willow chips are mainly used in larger combined heat and power or heating plants today. Such plants usually mix wet biomass with other biomass. Lately, willow chips are used in smaller plants as well. Smaller plants require drier biomass. Willow chip producers have good knowledge what quality is requested of heating plants. However, little is known about how factors such as time of harvest and shoots age (diameter), soil type and different varieties affect fuel quality. Although there has been a lot R & D projects on willow, there is no data on how various factors affect the humidity and fuel quality such as how water levels vary in a willow cultivation during the year or how shoots age (diameter) affects the quality. The project aims to develop knowledge how different parameters affect willow wood fuel properties in order to optimize harvest and control the correct range to the right user.	£47,778
Development of driving wheels on the willow harvester BioBaler for increased use at low soil bearing capacity	To develop the willow market in Sweden, it is important that harvesting machines can be used in varying weather and soil conditions. One solution is to install driving wheels on the willow harvester. It applies, among other things, on the Beet harvester and has proven to be an effective way to improve accessibility. The goal of this project is to improve conditions for willow harvest in Sweden by developing the BioBaler so that it is less sensitive to low soil bearing capacity and service availability improves. A milestone of the project is to develop and adapt driving wheels to the BioBaler.	£1,966

Project title	Project summary	Public funding
Conditions for willow chips in smaller plants (0,1-5 MW) - storage/drying of willow, effect on slagging and fouling	There are currently several major investments in technology for willow production in Sweden, especially in the harvest side. New harvesting systems are now in the market where the willow is harvested and processed and naturally dried in bales/bundles. Knowledge of how willow fuel characteristics changes depending on the storage and drying, formation of fouling, corrosion due to alkali, etc., are not fully explored and uncertainties exists. R & D projects are needed to increase knowledge for those who wish to use the willow as a single fuel in small heating plants. The project aims to develop knowledge of willow wood chip fuel properties. More precisely, the goal is to study the effects of storage / drying of willow chips and storage of bundles/bales has on slagging and fouling/(high temperature corrosion). In addition, the goal is to develop a set of requirements and conduct a discussion of operational strategies and boiler technology with the use of willow in the size range 0.1 to 5 MW.	£70,940
Development of machinery for SRC management and harvest	The aim of the project is to improve production capacity, profitability and efficiency in salix cultivation with the help of improved mechanical technology. The project will improve parts of current technology and develop new technologies in the areas of weed control and fertilization. Improved technology in these areas can significantly increase salix production.	£310,855
Continued development of the HSAB Head for direct chipping of willow	Direct chipping is one of several harvest methods for willow and with the suggested changes in construction of the HSAB head this harvest technique will reach the step of commercialization. The goal of the project is to make final changes primarily on the drive and attachments on the heads for Claas and Krone forage harvesters which were constructed during 2010-2011 with financial support from the Energy Board. With the HSAB head the harvest cost can be lowered from about 45 SEK/m^3 to about 25 SEK/m^3 provided good field layout. A head for the JD forage harvester will be constructed. The HSAB head will be marketed in Sweden and in the EU on websites and via agricultural fairs I Sweden and abroad. The application for support is of for 1129 500 SEK and the total project budget is 1 882 500 SEK.	£72,393
Compressing whole stem harvester	The project intends to develop a prototype for a full-shot harvester for bundled Salix. The new harvesting system with direct bundling will increase the efficiency and fuel quality in the production chain from the field to the boiler. The players in the industry are then given financial incentives and reasons to increase the cultivation and use of salix. The project is a direct continuation of previous efforts by the Swedish Energy Agency.	£359,060

Project title	Project summary	Public funding
Effects of plant material and planting on willow establishment/growth	The most important prerequisite for a sustainable willow biomass production is a successful stand establishment. Successful establishment implies a fast and even shoot development. The purpose of this project is to study different methods of willow establishment. In current commercial practise, willow is established by means of planting 20 cm long cuttings. Cutting length, thickness and (clonal) origin may be varied, but also the way of planting: A lay flat system, employing entire rods, may be used, but rods may also be fractionated into longer or shorter (billets) parts before putting them in furrows and covering them with more or less soil (which will affect relative emergence time and other performance measures). We employ controlled box experiments to predict the effects of planting material and way of planting on establishment, early growth and competitive performance in the field, and will test the most promising combinations in full scale field experiments.	£156,752
Large scale billet harvesting, drying and processing	The aim is to evaluate the system of billet harvesting, drying and processing by machines based on sugar cane technology, especially Case IH 7000, which has been in use in Britain for several years. Willow is harvested in the form of billets which are stored during the summer in large heaps during. The water content drops from about 55% to 35% or below. The fuel is reprocessed into a very fine chip of 2-5 mm which is delivered mainly to large coal fired power stations. The harvest system will be evaluated from technical and economical point of view for possible introduction in Sweden. Possible markets in Sweden are heat plants with high demand for dry and very fine fuel as well as pellet producers. The evaluation will be done during two visits to Great Britain during the summer and autumn of 2010 when harvest, storage and reprocessing will be studied. The capacity will be measured/studied in other ways and samples of the end product will be taken for fuel analysis and for demonstration to some possible Swedish end users.	£6,068
SRC harvest using forest operations machinery	The objective is to evaluate if conventional forest machines for thinning operations can be cost efficient when harvesting delayed (over-grown) Willow plantations, and if so, what technique is most suitable. The project will be performed in three steps: 1) a market study and a compilation of forest technology “convenient” for harvesting Willow, 2) a “brain storming” meeting were we presents the results from step 1 and discuss this field with invited people from the industry, e.g. farmers and machine builders, 3) a field study were conventional forest harvesting systems for felling and bunching and hauling to road side are studied in delayed Willow plantations which the results then are compared to litterateur data on conventional harvesting machines for Willow plantations.	£55,128

Project title	Project summary	Public funding
Systems for harvest with direct chipping of salix	The aim is to develop a more robust system for salix harvest with direct chipping including improved availability. The system of direct chipping is suitable for large scale operations and continuous large deliveries of energy chips. The activities in the project are: § A new harvester head will be developed which with only minor adjustments will fit any make of forage harvesters on the Swedish market. § Technical upgrading package for the forage harvesters Claas Jaguar and Krone from maize/grass to salix, especially regarding the feeding and the field floatation. § Field testing, primarily during the spring and autumn of 2010 in different salix growing areas in Sweden. This will be done in co-operation with Lantmännen Agroenergi and other actors on the Swedish salix market. Henriksson Salix AB has 20 years experience in harvesting technique for salix out of which the latest 10 year with Claas Jaguar. The project is a co-operation with JPS Maskin who has experience of Krone forage harvesters.	£158,205
Pre-study - Train transport and terminal handling of Salix	The aim of this prestudy is to give an overview of transports of biomass fuels on railway. On the basis of Skogforsks ongoing project ”Train terminals” conclusions will be drawn on possibilities of co-handling with forest fuels, design of effective terminals and costs for terminals and transports of relevance regarding Short Rotation willow, as chips and bundles, and of interest for the agricultural sector. The objective is to use the prestudy for planning a study of mobile terminal handling of willow to be carried out as part of a project part on mobile temporary terminals, with active participation from parties from the agricultural sector.	£111,11

Source: Swedish Energy Agency, 2019c

A1.6.2 Previous attempts to address such challenges

Information campaigns with willow SRC experts (researchers, entrepreneurs etc) from all parts of the value chain were organised in different parts of Sweden addressing to farmers all issues concerning willow SRC cultivation during the stagnating period of 2000-2010 when very few new plantations were established. The seminars were financed by the Swedish Board of Agriculture in order to make farmers that had not yet planted willow more acquainted to the “new” crop and to tackle the bad reputation by sharing good experiences from other farmers.

Discussions and long-term agreements on local level between biomass producers (the farmers) and end buyers (e.g. managers of small and medium-sized district heating plants) were proved important for keeping up some interest for SRC. Such discussions were usually initiated by the local actors themselves. In addition, there were initiatives initiated by e.g. the Swedish Board of Agriculture and the Swedish Energy Agency to promote such agreements to decrease the perceived risks among farmers. Several counties or municipalities made ambitious undertakings to increase locally produced “green” energy, and could offer long-term contracts for buying willow SRC wood chips.

Research and development projects with focus on developing new harvest techniques that would fit market needs have been financed by the Swedish Energy Agency that supported private companies to continue working with these issues.

During the first cutting cycle for willow SRC lower yields and incomes are expected and the first income will come after 4 years or more. Therefore, the introduction of an establishment subsidy can help to reduce the initial investments, reducing the risks taken by the farmer and making the option of planting willow more appealing. The current establishment subsidy covers approximately half of the planting costs, and it is surely not a game changer making farmers grow SRC instead of other crops, but it helps to decrease the economic risk for the farmers.

Woodfuel demand is fundamental as a driving force to spread SRC willow cultivation, and in this respect no policies other than taxation on fossil fuels were specifically implemented in order to ensure a demand for energy crops in Sweden. There is a consensus in Sweden concerning the importance of these measures for converting the energy system towards renewable biofuels.

A.1.7 Recommendations

The by far most important recommendation based on the Swedish experience in SRC willow would be to keep a strong focus on the farmer´s profitability. A focus on optimisation of biological productivity or maximising the environmental benefits from SRC will likely fail to optimize farmers profit, and hence reduce the farmers incentives to establish and grow SRC willow. Ecosystem services from SRCw, which have been found to be substantial and diverse, should primarily be considered and valued by society. If needed, society should establish incentives for farmers to grow SRC, but such incentives should be designed as to promote high yields rather than just large areas. Focusing on large areas will result in SRC being established on small, remote and infertile sites inevitably resulting in low yields and high production costs. This, in turn, will add to the bad will concerning SRC irrespective of the overall economy for the farmer, which might include subsidies for growing SRC.

A secondary objective would be to facilitate a multi actor market, i.e. to avoid trends towards monopoly among buyers and entrepreneurs. Such a monopoly-like situation has probably to a significant extent contributed to the market decline in Sweden.

A.1.8 Examples of successful Swedish business models

Here, we define a “successful” business models as business models resulting in high or at least reasonable profit for the farmer growing SRC willow.

i) Farmarenergi Grästorp: A group of SRC farmers growing and selling wood chips in the local district heating plant. Several farmers work together and one of the farmers is taking care of selling the woodchips to the local district heating plant producing approximately 10 GWh heat annually. SRC is combined with forest fuels if necessary. Average profitability for the SRC farmers is reported to be very high compared to conventional crops.

ii) Salixodlarna Örebro: A farmers co-operative consisting of 33 members producing willow in the same area and selling the chips to different end users (usually big power plants but also smaller district heating plants). The farmers have access to both direct chipping harvesters and whole shoot harvester enabling storing/drying of the fuel. The cooperative facilitates entrepreneurship among the farmers increasing overall profitability.

iii) Nynäs Gård Enköping: On a farm adjacent to the wastewater treatment plant of the Enköping municipality (approx.. 20 000 inhabitants) 76 ha SRC willows was planted in late 1990´s of which a large part is equipped with a drip irrigation system. During wintertime, some 20000 m^3 of wastewater from dewatering of sewage sludge is stored in ponds, and in summertime this water is mixed with tertiary treated wastewater and spread in the SRC willows. This results in an enhanced treatment efficiency and enhanced yield. The farmer is paid for receiving the wastewater, and the local district heating plant has bought the produced wood fuel. The system has resulted in a cost efficient improved wastewater treatment combined with recycling of plant nutrients as well as water, resulting also in locally produced biomass for energy. The system has attained national as well as international interest and goodwill both for the municipality and for the SRC as a viable crop. However, currently, the local district heating plant has reduced its consumption of wood fuel in favor of waste wood, which constitutes an obstacle for the local SRC producers.

A.1.9 References

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Appendix 2
Stakeholders consulted

Aberystwyth University
Agricultural and Horticulture Development Board
Buccleuch Estate
CONFOR
Coppice Resources
Crops4Energy
Crown Estate, Windsor
Euroforest
Forestry Commission
Iggesund
Miscanthus Nurseries Ltd
National Farmers Union
New Energy Farms
PGRO Processors and Growers Association
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