Hedgerow harvesting machinery trials report

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Contents

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Machinery Trials Report

1. Executive Summary

Hedgerows are a prevalent feature across Western Europe, with an estimated 700,000 km or 435,000 miles in Great Britain alone (Wolton, 2015). They have significant cultural and historical value and provide many functions and benefits within the landscape, including sheltering crops and livestock, supporting wildlife and linking habitats, controlling erosion and visually enhancing the landscape. Traditionally, hedges also provided a variety of wood products including firewood, but as labour became more expensive and wood was replaced by fossil fuels the practice of managing hedges for firewood was lost. Managing hedges for woodfuel through coppicing therefore provides an opportunity to rejuvenate old hedges, restoring not only their economic role but their value to the wider landscape. Despite increasing interest in managing hedges for woodfuel, there is limited data and knowledge regarding the productivity, practicality and logistics of such systems.

As part of the TWECOM Project (www.twecom.eu) The Organic Research Centre has undertaken hedgerow harvesting machinery trials at two sites in southern England during winter 2014/15. The aim of the trials was to assess the feasibility, efficiency, costs and viability of mechanising the process of coppicing hedges and processing the resultant hedgerow material as a local and sustainable source of woodfuel. The selection criteria for the hedgerow harvesting machinery was a range of sizes of machinery, with the associated range of hire or purchase cost, and a range of cutting mechanisms to investigate the impact on stem cut and stool regrowth. Machinery was loosely classified as small, medium and large scale, and one machine of each scale was trialled at each of the two sites, Elm Farm and Wakelyns Agroforestry. The large-scale harvesting machinery trialled were hydraulic shears and felling grapple with integral chainsaw; medium-scale were assisted fell (man with chainsaw and excavator) and tractor-mounted circular saw; and small-scale was manual fell (two men with chainsaw). Two scales of chippers were trialled; a large drum chipper and a small disc chipper.

Knowledge gained from these machinery trials has been consolidated into two publications; an EU best practice guide on hedgerow harvesting machinery and methods (available at www.twecom.eu) and an England-focused guide, which draws on the trials carried out by ORC (available at http://tinyurl.com/TWECOM). These publications are aimed at farmers and landowners, agricultural and forestry contractors, conservation organisations and local authorities interested in managing hedges for woodfuel, and focus on the logistics and practicalities as well as the methods and machinery selection. This report provides more detail on the methods, results and conclusions from the two machinery trials carried out by the ORC.

Key conclusions from the trials are:

- Every hedge is different, so it is difficult to produce precise costs for the various elements of the process. Every hedge has to be assessed and managed on its own merits.
- Assisted fell is a very quick and effective felling method, making best use of both manual and mechanised felling techniques, with the excavator able to take the brunt of the physical work in extracting and moving the hedgerow material as full length stems ready for processing, but demands a very experienced team who are used to working together because of the health and safety concerns of this coppicing method.

- Assisted fell and large chipper was found to be the most cost-effective harvesting and processing combination of all the machinery methods trialled when at least 280m of hedge was coppiced.
- Both the hydraulic shears and felling grapple with integral chainsaw options are likely to be better suited to large diameter single stemmed material. Single blade circular saws are optimally designed for small diameter material or short hedges which are less than 4m in height.
- The assisted fell and manual fell methods have the flexibility to work on most sites and hedges, because the chainsaw has the manoeuvrability to cope with the contours of coppice stools or hedgebanks. The manual fell method is however not suitable where there are large single-stemmed trees or where the hedge is more than approximately 5m tall, whereas the assisted fell method can handle pretty much all sizes of timber material.
- Due to the high proportion of twiggy material with a high percentage of bark, hedgerow woodchip will likely have a higher ash content than round-wood woodchip from forestry operations. Removing cordwood from coppiced material before chipping is therefore likely to negatively impact the quality of the woodchip produced. Hedgerow woodchip may also contain a higher percentage of fine material and long shards or slithers.
- The trials demonstrated that woodchip of reasonable quality which meets industry standards (P16B and G30 grades under BS EN and ÖNORM woodfuel standards respectively) can be produced from hedgerows. It is however important that the woodchip is matched to the right boiler able to cope with the variable nature of hedgerow woodchip, such as fines, shards and higher ash content.
- Economically, it is better to use the woodchip produced from hedges on-farm than to sell it. However it has been demonstrated that there is a market for hedgerow woodchip to owners of larger woodfuel boilers or woodfuel hubs of £18-20/m^3 (£72-80/t or €99-110/t) at 30% moisture content.
- Hedgerow flailing costs £0.88/m; over 15 years this amounts to £13.20/m. For a farm with 10 miles or 16.1km of hedges, where half are managed by coppicing for woodfuel and 400m are coppiced every year, £29,880 could be saved in reduced flailing costs over 15 years, not including the potential cost savings from using the woodchip as fuel or the income generated from the sale of the woodchip.
- The unit energy cost of hedgerow woodchip produced ranged from 1.4 to 3.9 pence per kilowatt hour (p/kWh) depending on machine options and hedge type, and would seem relatively favourable when compared to the cost of other woodfuels (3.43-5.21p/kWh), fossil fuels (3.5-8.33p/kWh) and electricity (12p/kWh) (Forest Fuels, 2015). Using woodchip from hedges on-farm could therefore not only incur savings from reduced flailing but also provide low cost energy, as well as rejuvenate hedges and support wildlife.
- Farmers are in a great position to establish woodfuel hubs, waste recycling facilities or local firewood or woodchip enterprises. These sorts of businesses are ideally suited to being locally based, minimising transport costs and therefore firewood and woodchip prices and providing much needed rural employment.

2. Introduction

Hedgerows are a prevalent feature across Western Europe, with an estimated 700,000 km or 435,000 miles in Great Britain alone (Wolton, 2015). They have significant cultural and historical value and provide many functions and benefits within the landscape, including sheltering crops and livestock, supporting wildlife and linking habitats, controlling erosion and visually enhancing the landscape. Hedgerows provide a habitat similar to that of woodland edge across agricultural landscapes, providing wildlife refuges from more intensive land use and connecting areas of semi-natural habitat. Many species live in or use hedges, with more than 600 plant species, 2000 insect species, 64 bird species and 20 mammal species associated with British hedgerows (Wolton et al, 2013). In the UK Hedgerow Habitat Action Plan, 84 of the species associated with hedgerows are of conservation concern (Maudsley, 2000).

Traditionally, hedges also provided a variety of wood products including firewood, but as labour became more expensive and wood was replaced by fossil fuels the practice of managing hedges for firewood was lost. Following recent rises in oil and gas costs and concerns about climate change, there is growing interest in reviving the economic value of hedgerows through managing them once again for woodfuel. Most UK hedges are currently managed by annual flailing, a costly practice which eventually leads to degradation of the hedge without periodic rejuvenation by laying or coppicing. Likewise, under-management, where the hedge is left to develop into a line of trees, also results in the loss of hedgerows. Managing hedges for woodfuel through coppicing therefore provides an opportunity to rejuvenate old hedges, restoring not only their economic role but their value to the wider landscape.

Despite increasing interest in managing hedges for woodfuel there is limited data and knowledge regarding the productivity, practicality and logistics of such systems. As part of the TWECOM Project (www.twecom.eu) The Organic Research Centre (ORC) has therefore undertaken hedgerow harvesting machinery trials at two sites in southern England during winter 2014/15 to assess the feasibility, costs and efficiency of using both large-scale and small-scale agricultural and forestry machinery and methods to harvest hedges for woodfuel. Although other trials using small-scale techniques such as manual felling with a chainsaw have been carried out in Devon, south west UK (Wolton, 2012), these trials are believed to be the first in the UK to assess the feasibility of harvesting woodfuel from hedgerows using large-scale machinery. As part of the TWECOM project machinery trials were also conducted by other TWECOM partner organisations in Belgium: Agrobeheercentrum Eco2 and Inagro, where roadside hedgerow trees and field boundary and ditchside rows of alder trees were harvested.

Knowledge gained from the TWECOM machinery trials has been consolidated into two publications; an EU best practice guide on hedgerow harvesting machinery and methods and a UK focused guide on harvesting woodfuel from hedges which draws on the trials carried out by ORC. These publications are aimed at farmers and landowners, agricultural and forestry contractors, conservation organisations and local authorities interested in managing hedges for woodfuel, and focus on the logistics and practicalities of managing hedges for woodfuel as well as the methods and machinery selection. This report details the methods, results and conclusions from the two machinery trials carried out by the ORC.

2.1. Hedgerow harvesting machinery

The aim of the ORC's TWECOM trials was to assess the feasibility, efficiency, costs and viability of mechanising the process of coppicing hedges and processing the resultant hedgerow material as a local and sustainable source of woodfuel. The aim was to trial both large-scale and small-scale agricultural and forestry machinery and methods in contrast to the predominantly manual methods which had been assessed previously through the Cordiale Project (Wolton, 2012). In the Cordiale trials the costs of hedgerow harvesting and the volume of timber produced had been investigated for the two traditional hedge management techniques of hedgelaying and coppicing, both carried out using the motor manual method of a man with a chainsaw. The timber was extracted as log and brash (to be burnt in the field), and as woodchip respectively, referring to these practices as lay and log, and coppice and chip.

The selection criteria for the hedgerow harvesting machinery for the ORC trials was a range of size of machinery, with the associated range of hire or purchase cost, and a range of cutting mechanisms to investigate the impact on stem cut and stool regrowth. It was decided to divide machinery loosely into small, medium and large scale, with the aim of trialling one machine of each scale at each of the two trial sites, Elm Farm and Wakelyns Agroforestry.

Many different machines and combinations of machines can be used for harvesting hedgerows mechanically; most types of timber harvesting machinery can be classified by their cutting mechanism (Figure 2.1).

A. **Hydraulic tree shears:** These cut or fell trees using hydraulically-powered shears or steel blades to slice through the timber and are usually integrated into a timber grab, feller-buncher or accumulator arm to hold and manipulate the felled tree and are typically excavator mounted.
B. **Integral circular saw**: Although not covered in these trials due to a lack of availability, these can be found in forestry harvesters such as the Bracke Forest C16.c (www.brackeforest.com) and are usually integrated into a timber grab with a feller-buncher or accumulator arm function and typically excavator mounted.
C. **Integral chainsaw cutting bar:** These are most often found in smaller bioenergy felling heads or felling grapples, and are generally accompanied by some kind of timber grab and typically excavator mounted.
D. **Circular saw:** These are generally tractor-mounted on a hedge cutting arm, and can include 1- 4 circular saw blades. They are also known as shaping saws.
E. **Manual chainsaw:** Aside from a manual bowsaw this is the most basic, yet versatile, felling machine, and comes in a variety of sizes, with regards to horsepower and chainsaw bar length, depending on the size of timber and situation.

Figure 2.1. Different types of timber harvesting machinery: A) hydraulic shears, B) integral circular saw, C) integral chainsaw cutting bar, D) circular saw, E) chainsaw.

2.2. Hedgerow processing machinery

As with the harvesting machinery, the selection criteria for the processing machinery for the ORC trials was a range of size, with the associated range of hire or purchase cost, and a range of processing options which produce different timber products for different markets (Figure 2.2). The following hedgerow material processing methods were trialled:

F. **Whole-tree chipping to produce woodchip.** All of the hedgerow material coppiced from a section was fed through a chipper to produce woodchip. Medium-scale drum chippers and small-scale disc chippers were compared.
G. **Whole-tree chunking to produce bags of small diameter logs and kindling ready for market.** A tractor-mounted Welmac UK TR110 branch logger was used to process whole-tree hedgerow material from a hawthorn hedge at Elm Farm (www.welmacuk.co.uk)
H. **Extraction of hedgerow cordwood for processing into firewood logs.** This was done by extracting the larger diameter cordwood down to approximately 4"/10cm diameter from the pile of coppiced hedgerow material using a predominantly manual method and a chainsaw, and when necessary using a tractor-mounted fork to open up the pile of material.

Only small-scale trials of whole-tree chunking and firewood processing were conducted, with limited data being produced. The focus of the processing trials was on chipping whole-tree hedgerow material to produce biomass woodchip for the woodfuel boiler market.

With regards to chipping the hedgerow material, the aim was to trial different size machines which operate at completely different scales and vary considerably in their hire and particularly purchase costs. Medium-large scale chippers are generally drum chippers designed to chip whole tree material or large diameter cordwood for the woodchip market, whereas small-scale chippers used by landscapers and tree surgeons are designed to process arboricultural arisings for ease of transport and disposal, and are generally disc chippers (Figure 2.2F).

Figure 2.2. Different hedgerow material processing options: F) whole-tree chipping (left: drum chipper; right: disc chipper), G) whole-tree chunking, H) extraction of cordwood

3. Methods

3.1. Trial hedgerow selection

The ORC hedgerow harvesting machinery trials were held at two different locations; Elm Farm near Newbury in West Berkshire in December 2014 and Wakelyns Agroforestry near Diss in Suffolk in February and May 2015. Three different hedges were used, representing a range of physical characters. At Elm Farm and Wakelyns Agroforestry hedgerows were chosen for inclusion in the trials based on a number of factors:

- The stage in the hedgerow management cycle (Hedgelink, 2008). Hedges at a suitably mature stage for coppice management were selected, i.e. of enough biomass to warrant woodfuel production.
- Predominantly suitable species for coppicing and for woodfuel production.
- Sufficient length of hedge and reasonably consistent in character to trial a number of machines.
- Ease of access to the hedge and minimum distance from a surfaced road or track for management activities and the trial machinery so as to minimise damage to farmland.
- Ground conditions adjacent to hedge sufficiently good to cope with trial machinery traffic without undue damage to grazing land.
- No screening or boundary function to avoid potential future hedgerow management conflicts.
- No signs of hazel dormice recorded, so coppicing work not affecting confirmed dormouse habitat.
- Condition of hedgerow fence; ideally in need of replacement.

Elm Farm

Elm Farm is an 85 hectare organic livestock farm in the south east of England. The farm has an average annual rainfall of 71cm. The soil type is mainly Wickham Series clay, poorly drained clay loams susceptible to structural damage. The hedges on Elm Farm have not been actively managed for a number of years (approximately 36-37 years), asides from occasional side flailing to maintain field sizes and statutory roadside management. There are 45 separate hedges on the farm with a total length of approximately 9.5km (Figure 3.1). Results from a survey of all hedges on the farm carried out in July 2013 show that the dominant woody species is Blackthorn (*Prunus spinosa*), with other commonly recorded species being Hawthorn (*Crataegus monogyna*), Hazel (*Corylus avellana*), Goat Willow (*Salix caprea),* Grey Willow *(Salix cinerea*) and Oak (*Quercus robur*). Blackthorn, bramble and dog rose outgrowth is also common, resulting in wide unruly hedges up to 10m in width, often with ditches and existing fences being engulfed by this shrubby outgrowth.

Hedge 21

At Elm Farm the hedge selected for the machinery trials (Hedge 21, Fig. 3.1 and 3.2) was a tall, dense roadside hedge on the western side of a single track road, Park Lane, predominantly consisting of mature hazel coppice stools with substantial blackthorn outgrowth and a number of multi stemmed field maple trees, which showed signs of having been laid in the past. The hedge is thought to have last been coppiced around 28 years ago. This hedge was chosen due to its suitable growth stage for coppicing, good firm ground conditions, easy access with direct access off the road and its uniformity in species composition and structure. Although the road side of the hedge has been flailed annually, recent management has been minimal, leaving the hedge to become large and overgrown. On average the hedge was 6m in height, 3-5m wide (including the blackthorn outgrowth) and 240m in length.

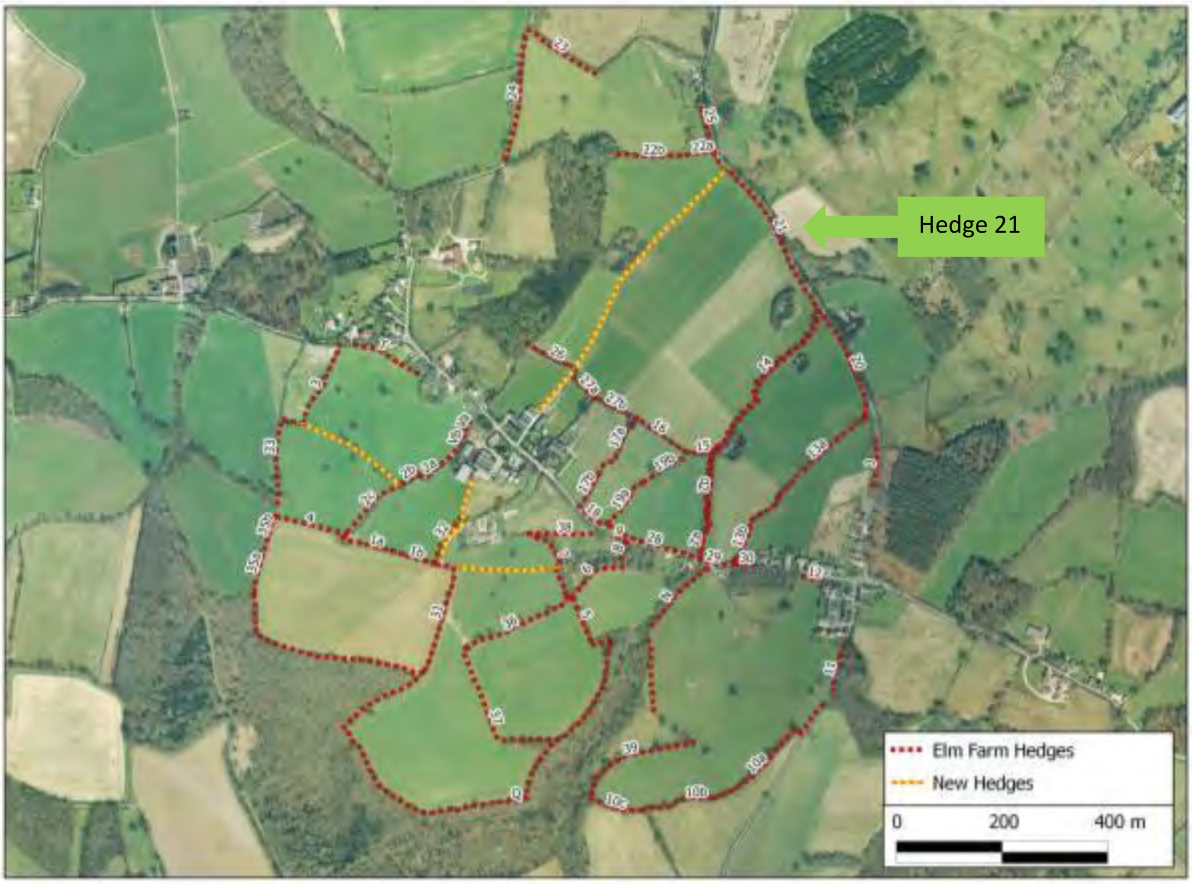

Figure 3.1. An aerial map of the hedgerow network at Elm Farm depicting both existing and newly planted hedges, and Hedge 21 where the machinery trials were carried out.

Figure 3.2. Hedge 21 at Elm Farm before coppicing.

Wakelyns Agroforestry

Wakelyns Agroforestry is a 22.5ha diverse organic agroforestry system in eastern England which incorporates four silvoarable systems; short rotation coppiced (SRC) willow, SRC hazel, mixed top fruit and nut trees, and mixed hardwood trees with 10-12m wide crop alleys between tree rows. Average annual rainfall for the area is 606 mm, average annual sunshine is 1535 hours, average annual minimum temperature is 6.0 °C and average annual maximum temperature is 13.8 °C (Met Office East Anglia 1971-2000 averages). The soil type is clay loam over chalk with clay content of 25-30%, pH 8.0, organic matter approximately 3.5%, and low indices for phosphorus (P) and potassium (K). Hedges on the farm are mixed species and have been left to grow tall over the last 30 or so years.

Figure 3.3. The hedgerow network at Wakelyns Agroforestry showing the location of the machinery trial hedges: Hedges 1 and 2.

Hedge 1

The main hedge chosen for the machinery trials at Wakelyns Agroforestry was a tall, gappy hedge on the eastern side of a green lane (Figure 3.3 and 3.4), consisting mainly of small field maple trees and hawthorn and some blackthorn, dogwood and bramble undergrowth. This hedge was chosen based on its suitable growth stage for coppicing, easy access, reasonable uniformity and favourable ground conditions. On average the hedge was 7.5m in height, 3.5m in width and 110m in length. The hedge had been left to grow up for 20 years and the field maples were approximately 35-45 years old.

Figure 3.4. Hedge 1 used in the machinery trials at Wakelyns Agroforestry

Hedge 2

In addition to Hedge 1 a second hedge was chosen for the trials at Wakelyns Agroforestry. Hedge 2 is a sparsely planted hazel coppice hedge with several small multi-stemmed field maple trees and is located on the western side of the green lane directly opposite to Hedge 1 (Figure 3.3 and 3.5). On average the hedge was 4m in height and 2m wide, and had been coppiced approximately 15 years ago. Only a 20m section of this hedge was coppiced.

Figure 3.5. Hedge 2 at Wakelyns Agroforestry

3.2. Other considerations when coppicing a hedge

Timing

When planning the coppicing work we considered the timing with regards to the impact on adjacent farmland, wildlife which uses hedges to live in and move along, and regrowth of the coppiced stools and trees. Ground conditions generally start to deteriorate from October and often remain wet and soft until March, depending on the soil type, with conditions more challenging at Elm Farm than Wakelyns. The bird nesting season is taken from the beginning of March and dormice start to rouse from hibernation in late April. Most trees and shrubs are best coppiced in the winter, when the sap is down, and maximises the chance of successful and vigorous regrowth.

Recommendations are to coppice hedges between 1st September and 30th April, in line with DEFRA's Cross Compliance rules. Coppicing can take place either in late autumn, as soon as most of the leaves have fallen and before the ground gets too wet, or in late winter when the ground starts to dry out, depending on the weather and ground conditions each winter. If hedges are coppiced in autumn, coppiced material should ideally be left out in the field so the leaves fall off before chipping. Coppicing in late winter (January/February) allows birds to make good use of the hedgerow berries over the winter, although coppicing after the end of February should be avoided if at all possible because of the nesting season for birds and small mammals.

Legal requirements

Cross Compliance

The cross compliance rules and regulations were taken into account when planning the timing of the hedgerow coppicing trials, so that the ORC trials were in line with current regulations and followed best practice. Farmers and landowners in England claiming rural payments from the government under the Basic Payment Scheme, Countryside Stewardship, and certain elements of the English Woodland Grant Scheme, need to comply with DEFRA's cross compliance rules. These state that under GAEC 7a you must not cut or trim a hedgerow or tree between 1st March and 31st August, unless it is to carry out hedgelaying or coppicing during the period 1st March to 30th April (inclusive). Traditional hedge banks must not be cast up for maintenance between 1st March and 31st August. More information is available at www.gov.uk/government/collections/cross-compliance.

Tree Preservation Orders (TPOs) and Conservation Area

The local Planning Authorities were contacted to ascertain whether any of the trees to be felled or coppiced as part of the hedgerow coppicing trials had a Tree Preservation Order (TPO) on them or were in a conservation area. West Berkshire Council had an online map which showed the locations of all TPOs, whilst the Tree Officer at Suffolk Council Waveney District Council in Suffolk was contacted to ascertain the same. No TPOs were present on any of the trees in the hedges identified for the hedgerow harvesting trials, and the hedges were not in a conservation area.

Felling licence

Consideration was given to the need for felling licences for the proposed hedgerow coppicing, and at both Elm Farm and Wakelyns the local Forestry Commission Woodland Officer visited the site to see the hedges and assess the need for felling licences. A felling licence from the Forestry Commission is necessary before coppicing where hedge stems are 15cm or larger in diameter when measured at breast height (dbh is measured 1.3m from the ground) and when more than 5m^3 of timber is to be felled in any one calendar quarter, reducing to 2m^3 if any of the wood is to be sold. This licensable diameter reduces to 8cm or larger in diameter if felling single stems such as hedgerow trees. See the Forestry Commission website for more information: www.forestry.gov.uk.

In order to ascertain whether a felling licence was required, the diameter of the larger stems (those single stemmed trees over 8cm diameter at breast height (dbh) and the stems of multi-stemmed shrubs and coppice stools over 15cm dbh) was measured using forester's callipers. The stem height to the point where the main trunk branches was estimated, and using a table of timber volume calculations the volume of these larger stems was calculated (Hamilton 1975). The volume of all the licensable stems in each trial hedge was totalled to ascertain whether it was more than $2m^3$ for Elm Farm, where the woodchip would be sold, or $5m^3$ for Wakelyns Agroforestry, where the woodchip would be used on-site in their woodfuel boiler.

It was decided that a felling licence was not necessary at Wakelyns because less than $5m^3$ of licensable diameter timber was due to be felled during the hedgerow coppicing trials. At Elm Farm, however, because of deteriorating ground conditions, it was not certain until very late on which hedge was to be coppiced as part of the trial, and so felling licences were applied for a couple of hedges where it was necessary. Finally Hedge 21 was coppiced which did not require a felling licence because the majority of the timber was multi-stemmed and less than 15cm in diameter, but the felling licences obtained remain valid for 10 years, and so can be used at a later stage in the Elm Farm hedgerow coppice rotation plan.

Hedgerow Regulations 1997

With regards to both the Hedgerow Regulations 1997 and the Forestry Commission's requirements, coppiced hedges must be allowed to regrow, otherwise it is regarded as hedgerow removal, and need to be given adequate protection where necessary to ensure they do. This includes protection from herbicide spray drift and deer and rabbit browsing.

European Protected Species (EPS)

As part of the assessment of the biodiversity implications of managing hedgerows for woodfuel, the ORC has surveyed the hedges at Elm Farm and dormouse surveys have been carried out since 2013. Hazelnuts with holes characteristic of being opened by dormice confirmed the presence of this species at Elm Farm and so the presence and habitat requirements of the dormouse were therefore also taken into consideration when selecting a hedge to be coppiced at Elm Farm. There are no records of dormice at Wakelyns Agroforestry.

The hazel dormouse is one of 22 species which are regarded as European Protected Species (EPS) and are covered by the Conservation of Habitats and Species Regulations 2010. These species include all 17 species of bat, hazel dormouse, great crested newt, otter, sand lizard and smooth snake. Several of these species may therefore be associated with hedgerows, and so need to be taken into consideration when planning any hedge management work, particularly if it has a significant impact on the hedgerow habitat such as coppicing or hedgelaying. These regulations therefore have implications for how hedgerows can be managed and operations carried out. For more information on EPS and the steps land managers should take to safeguard them see: www.forestry.gov.uk/england-protectedspecies.

For further details on the legislation surrounding the management of hedges and the coppicing of them for woodfuel, see the ORC publication: *A guide to harvesting woodfuel from hedges* available from The Organic Research Centre website at http://tinyurl.com/TWECOM.

Safety requirements

Road closure

As Hedge 21 at Elm Farm is a roadside hedge, running along the western side of a small single-tracked road called Park Lane, it was decided to apply for a temporary road closure permission from West Berkshire Council. This decision was made because it was not possible to be absolutely certain that some hedgerow material would not fall into the road, and the road was not wide enough for the trial hedgerow side to be cordoned off. Closing the road protected road users and removed any risk of damage to vehicles; it also allowed the contractors to work uninterrupted, without having to consider traffic movements, and enabled the low loaders to park for the day on the road. This emergency road closure permission took just a few days to organise and cost £61. However, if a more formal temporary traffic regulation order was required, it would have taken 3-10 weeks to organise and cost £1000-1500. We were required to put out road diversion signs on the morning of the trial and to remove them at the end of the day. These signs would have cost £500-600 to hire from Volker Highways, but they kindly lent them to ORC without cost. These road closure costs are not considered in the economic analysis of the trials.

Prior to the trials, ORC had to check that their public liability insurance covered the activities involved in the hedgerow trials, and were required to specify the activities being carried out. Risk assessments of the hedgerow coppicing and chipping work were carefully prepared by ORC to cover the contractors and staff involved, and in a separate risk assessment the visitors attending the trials. Copies of public liability and professional indemnity insurance, operators' qualifications and certificates and risk assessments for their work were obtained from all of the contractors involved in the trials in the weeks leading up to each trial. Safety measures were put in place to protect visitors at both trial sites, which included taping off a visitors' area a safe distance from the working machinery and taking a register of all people (staff, contractors and visitors) present at the trials.

Hedgerow preparation

Hedges often need preparing prior to coppicing, by removing fences and cutting back hedgerow outgrowth. To prepare the hedge at Elm Farm prior to the coppicing trial, the extensive blackthorn outgrowth, which extended approximately 2m from the outer fence, was cut back with a flail hedgecutter, and the post and barbed wire fence was removed by pulling it out with the front fork on a tractor. This levelled up the hedge so that it was approximately the same width along its entire length, making each section more directly comparable with the others.

In addition, the remnants of three old wire fences were removed from within the hedge. This was done thoroughly and manually with a team of 6 people (3 ORC staff and 3 West Berkshire Countryside Society volunteers), using wire cutters and heavy leather gloves to extract every single piece of wire we could find. The few pieces of wire that couldn't be removed because they had grown into the stems of shrubs were left and marked with orange spray paint, so that they could be cut out separately and put to one side. This thorough metal removal work was done to minimise the chances of any metal damaging the harvesting machinery or chippers, having received a warning from one of the chipping contractors that ORC would be liable for the cost of any damage to their machine.

To prepare the hedges at Wakelyns Agroforestry prior to the coppicing trial, much less needed to be done. The trial sections of the hedge were thoroughly inspected for any metal or wire, but none was found; there were no remnant fences present within or alongside them which needed removing. There was some bramble outgrowth which extended up to 2m in places; this was cut back with the circular saw prior to the coppicing trials.

Pre-trial hedgerow assessments

Hedgerow assessments were carried out for each trial hedge immediately prior to the trials. These assessments included: hedge size (average height and width), woody species composition (estimated proportion of each species), stem density and total hedgerow biomass. These measurements were taken for monitoring purposes, so that the impact of hedgerow coppicing could be ascertained. Hedgerow biomass estimations were made using a tool developed by Rob Wolton with assistance from Chris Clare (Project Silvanus) on behalf of the Tamar Valley AONB and the Devon Hedge Group. This biomass estimation tool can be found at:
http://www.devon.gov.uk/index/environmentplanning/natural_environment/biodiversity/devon_hedges/hedges-for-wood-fuel.htm
Hedgerow ground flora and invertebrates were also monitored for their diversity and abundance. These pre-trial hedgerow assessments have been written up in a separate report, Hedgerow coppicing impacts on microclimate, biodiversity and regrowth (Westaway et al, 2015).

3.3. Trial machinery selection and specification

Table 3.1 below shows the harvesting and processing machinery options that were selected for the two hedgerow harvesting trial sites.

Table 3.1. Summary of the selected machinery options and contractors used in the ORC hedgerow harvesting machinery trials at Elm Farm and Wakelyns Agroforestry

Elm Farm Harvesting Machinery			
Scale	Cutting mechanism	Machinery/method	Contractor
Large	Hydraulic shears	Dymax 10"/25cm tree shears	Practicality Brown
Medium	Chainsaw	Assisted fell technique	Englefield Estate
Small	Chainsaw	Manual fell	Englefield Estate
Wakelyns Harvesting Machinery			
Scale	Cutting mechanism	Machinery/method	Contractor
Large	Integral chainsaw cutting bar	Gierkink GMT 035 felling grapple	Marshall Agricultural Engineering
Medium	Circular saw	Single Fisher Humphries 36”/90cm circular saw	PJ & MJ Ward Contracting
Small	Chainsaw	Manual fell	PJ & MJ Ward Contracting
Elm Farm Processing Machinery			
Scale	Cutting mechanism	Machinery/method	Contractor
Large	Drum chipper	Heizohack HM 8-500 K 28”/71cm fuel grade drum chipper	Wessex Biofuels Ltd
Small	Disc chipper	Timberwolf TW 150 DHB 6”/15cm disc chipper	Morrison Tree Surgery & Fencing Contractors Ltd
Wakelyns Processing Machinery			
Scale	Cutting mechanism	Machinery/method	Contractor
Large	Drum chipper	Jenz HM360 14”/36cm drum chipper	Peter Frizzell Ltd

Harvesting machinery

Hydraulic tree shears

A Dymax 10”/250mm grapple tree shears with added accumulator or feller buncher functionality mounted on an 8 tonne Komatsu PC78-6 zero swing excavator was used as the large-scale hedgerow harvesting machinery option for the Elm Farm trial (Figure 3.6). These tree shears just need one double acting shear/hammer hydraulics circuit, which is found as standard on most excavators. They do not need a third hydraulic service, which many machines would not have as standard (www.treeshears.co.uk).

Figure 3.6. Excavator mounted 10”/250mm Dymax tree shears coppicing Hedge 21 at Elm Farm

The excavator and Dymax tree shears were hired with an experienced operator from Alistair Beddall of Practicality Brown Ltd, based near Slough in south Buckinghamshire. Practicality Brown is the UK distributor for Dymax tree shears. Dymax tree shears are available in a range of sizes from 10-14"/250-350mm and can be mounted on 8-20 tonne excavators depending on the size of material to be coppiced, the reach required and the ground conditions. Larger tree shears are also available, such as the Westtech Woodcracker (www.westtech.at) which has models which can fell trees from 14-24”/350-600mm diameter.

Felling grapple with integral chainsaw cutting bar

Figure 3.7. The felling grapple with integral chainsaw cutting bar: Excavator mounted Gierkink GMT 035 felling grapple, coppicing Hedge 1 at Wakelyns Agroforestry

A Gierkink felling grapple GMT 035 with integral chainsaw cutting bar mounted on a small 5 tonne Kubota excavator (www.gierkinkmt.nl) was used as the large-scale harvesting machinery option for the Wakelyns Agroforestry trial (Figure 3.7). This felling grapple was hired with an operator from Marshall Agricultural Engineering, a forestry and agricultural machinery dealer in Hartfield, East Sussex.

The Gierkink GMT 035 is one of several bioenergy felling heads available. These are generally small-medium sized timber grabs with either integral shears or chainsaw cutting bar such as the Mecanil XG220 energy wood head (www.mecanil.fi) or the Biojack 400S (www.biojack.fi).

Circular saw

A 36"/900mm mechanically-driven single blade Fisher Humphries circular saw, mounted on a Massey Ferguson 390 tractor was used as the medium-scale harvesting machinery option for the Wakelyns Agroforestry trial (Figure 3.8). A second 50 horse power tractor with a front-mounted fork was used to move hedgerow material after coppicing and felling. This front-mounted fork comprised a Massey Ferguson 820 front end loader and farm-built two-pronged fork, built using two 48"/1200mm muck fork tines set about 48"/1200mm apart with a hydraulic centre-mounted top grapple arm. This circular saw and tractors were hired with experienced operators from PJ & MJ Ward Contracting, agricultural contractors based near Diss in Suffolk. Numerous makes of circular saw are available, both new and second hand; most are tractor-mounted on a hedge cutting arm. Because of the lack of directional control of the material being felled, they are generally used in combination with a second tractor or bulldozer with front-mounted fork to move material after felling.

Figure 3.8. The circular saw: A 36"/900mm mechanically-driven single blade Fisher Humphries circular saw, mounted on a Massey Ferguson 390 tractor with a front-mounted fork moving hedgerow material after coppicing Hedge 1 at Wakelyns Agroforestry

Multi-blade saws are also available such as the Bomford Turner ProSaw (www.bomford-turner.com) Kirogn tri-blade or 4-blade saw (www.kirogn.fr) or Protech single blade or tri-blade circular saw (www.protechmachinery.co.uk). Multi-blade circular saws are used for coppicing hedgerows by AJ Hawes & Family, specialist hedgecutting contractors based near Henley-on-Thames in Oxfordshire.

High speed hydraulically-driven multi-blade circular saws are apparently not so good for coppicing short rotation coppice willow, and a mechanically-driven single blade circular saw has been found to be better (anecdotal evidence from Paul Ward of PJ & MJ Ward Contracting Ltd). However Bomford Turner recommend their quad-blade ProSaw for coppicing hedges because they can have a longer cutting length than single circular saws, and are more powerful to cut through larger diameter material.

Chainsaw felling using assisted fell technique

The assisted fell technique here refers to a man with a chainsaw using the standard motor manual method of tree felling, but supported by an excavator with a front-mounted land rake (Figure 3.9). Assisted fell was used as the medium-scale harvesting machinery option for the Elm Farm trial, during which a Husqvarna 390XP chainsaw with a 24”/600mm cutting bar was supported by an 8 tonne Doosan DX80R excavator. Greg Vickers, the former Head Forester of Englefield Estate was contracted to take part in the trials, and he sub-contracted the work to Brian and Ricky Eaton, local father and son forestry contractors. Where smaller trees or coppice stems are being felled, a tractor with front-mounted fork or grab could be used instead of an excavator.

Figure 3.9. The assisted fell technique: chainsaw plus excavator mounted land rake coppicing Hedge 21 Elm Farm

Chainsaw felling using motor manual fell technique

The motor manual fell technique refers to a man with a chainsaw using the standard motor manual method of tree felling (Figure 3.10). Manual fell was used as the small-scale harvesting machinery option for both the Elm Farm trial and the Wakelyns Agroforestry trial. At the Elm Farm trial, a Husqvarna 560XP chainsaw with a 15”/425mm cutting bar was used, with one person cutting whilst the other was supporting the stems and extracting and stacking the material. Englefield Estate was contracted to take part in the trials, who sub-contracted the work to Jason Clarke and Bruce Morcom, local manual felling contractors. At the Wakelyns Agroforestry trial, PJ & MJ Ward Contracting were hired and provided two experienced chainsaw operators using Stihl 023 and 250 chainsaws, although they only used one chainsaw to coppice at any one time. This two man chainsaw team operated in much the same way as at Elm Farm, with one primarily cutting whilst the other supported and extracted the stems and timber.

Figure 3.10. The manual fell method: two person team with a chainsaw coppicing hazel at Hedge 21 Elm Farm

Processing machinery

Large scale crane-fed drum chippers

Large fuel grade biomass drum chippers were used as the large-scale hedgerow material processing option for both the Elm Farm trial and the Wakelyns Agroforestry trial.

At the Elm Farm trial a Heizohack HM 8-500 K fuel grade biomass drum chipper was used (Figure 3.11), which can chip up to 708mm/28" diameter timber (www.heizomat.de). It is a tractor towed PTO-driven chipper which weighs approximately 9 tonnes including the crane. It is mounted on a single axle chassis with one pair of normal road tyres, rather than wide or flotation tyres. The crane is mounted on the back of the tractor and is a telescopic Farmi 4571 crane. The chipper has an integral 35/40mm sieve to produce G30 chip. The Heizohack drum chipper and tractor was hired from Wessex Biofuels, a subsidiary of Wessex Woodland Management Ltd, a large woodland management company based locally near Hungerford, West Berkshire. They sub-contract the running of their chipper to Gary Thomson from Thomson Tree Services, who provided the tractor and experienced operator. A second large Massey Ferguson tractor was hired from Thomson Tree Services and an 11 tonne grain trailer was hired from Sutton Estates to transport the woodchip from the field adjacent to Hedge 21 to the storage barn at Elm Farm.

Figure 3.11. The tractor towed Heizohack HM 8-500 K fuel grade biomass drum chipper with telescopic crane chipping material from Hedge 21 at Elm Farm

Figure 3.12. The tractor towed Jenz HM360 fuel grade drum chipper with 8.6m telescopic crane chipping material from Hedge 1 at Wakelyns Agroforestry.

At the Wakelyns Agroforestry trial a Jenz HM360 drum chipper was used (Figure 3.12) which can chip up to 14”/360mm diameter softwood and 12”/300mm diameter hardwood. It is a tractor towed PTO-driven chipper which weighs 8-9 tonnes plus a 2 tonne crane mounted on a single axle chassis. Its ground pressure and impact on soft or sensitive sites had been reduced however by fitting extra wide 600mm flotation tyres. A telescopic crane with 8.6m reach had been retro-fitted where the standard crane has a reach of 4-5m. The chipper has an integral 35mm sieve as standard to produce G30 chip.

This chipper was towed by a Valtra T202 tractor. This Jenz drum chipper and tractor were hired from Peter Frizzell Ltd, a forestry and habitat management contractor based near Diss, Suffolk, and were provided with an experienced operator. A very small Massey Ferguson tractor and 4 tonne grain trailer with extended sides was hired from Wakelyns Agroforestry, and a second tractor and 3 tonne dump trailer were hired from PJ & MJ Ward Contracting, to transport the woodchip from the fields adjacent to Hedges 1 and 2 to the storage barn at Wakelyns Agroforestry.

Integral 35mm woodchip screen in the Jenz HM360 chipper, also found in the Heizohack chipper

Small scale manually-fed disc chipper

At the Elm Farm trial a manually-fed disc chipper was used as the small-scale processing machinery option to chip the remaining half of the hedgerow material in April 2015. A 6"/150mm TW 150 DHB Timberwolf disc chipper (www.timberwolf-uk.com) was used (Figure 3.13). This chipper is a standard landscaper's chipper, frequently used in the landscaping and tree surgery business by independent contractors doing small or domestic-scale work often in gardens.

Figure 3.123. The diesel powered 6" Timberwolf disc chipper being used to chip material from Hedge 21 at Elm Farm

It is self-propelled in that it has a Kubota 4 cylinder 35 horse power diesel engine, so doesn't need a tractor or PTO shaft to drive it, but is road towable with a braked road chassis. It is very small and relatively light (737kg) and can be manoeuvred by hand into tight spaces, so is ideal for the garden situation or where there is limited vehicle access, being only 1.4m wide. As it is less than 750kg, it doesn't require a special licence from DVLA to tow it, which is why it is so popular with small-scale contractors. Its throughput is rated at 4 tonnes/hour, with two 101mm fully hardened steel blades and twin hydraulic rollers complete with auto feed or no-stress control. The chipper does not have variable intake speed control or any sieves or screens fitted as standard to prevent shards and splinters, though some disc chippers (such as TP chippers) can have these retro-fitted.

This Timberwolf chipper was hired from Morrisen Tree Surgery & Fencing Contractors Ltd, local contractors based near Hungerford, who provided two experienced operators. On the first day of chipping in April 2015 a 135hp Massey Ferguson 6613 tractor from Eling Farm and 11 tonne grain trailer from Kintbury Holt Farm was used to transport the woodchip from the field adjacent to Hedge 21 to the storage barn at Elm Farm. On the second half day Morrisen Tree Surgery's own tipper lorry was used to transport the woodchip to Elm Farm.

Small scale manually-fed whole-tree chunking machine

A TR110 Welmac UK branch logger was trialled at Elm Farm in April 2014 to process whole-tree hedgerow material from the hawthorn hedge trial plot at Elm Farm (www.welmacuk.co.uk). This small scale branch logging machine with automatic feeding system chops small diameter timber into short logs, feeding them straight into string bags ready for sale (Figure 2.2.G). They are designed and manufactured in the Czech Republic and imported and distributed by Welmac UK.

It is a tractor-mounted PTO-driven branch logger or chunker which chops small branches, trees and shrubs, up to a diameter of 5"/125mm for softwood and 4"/100mm for hardwood, into 6"/150mm lengths. It has twin hydraulic rollers complete with auto feed control, and runs optimally on a 70 horse power tractor with a two point linkage. This is the largest branch logger in the Welmac UK range, with others chunking 60-75mm timber into 5"/130mm lengths.

It is a relatively small and inexpensive piece of machinery, costing approximately £6,500+VAT, which can be operated in situations with limited access or space. Its throughput is rated at 60-100 string bags per hour. TR110 branch loggers can be hired at £70/day not including delivery, with the hirer needing to provide a tractor and operators.

3.5. Trial plots

Elm Farm

Large scale option: Hydraulic tree shears - 2 x 50m trial plots, plus a 22m warm up section

Medium scale option: Assisted fell technique - 50m trial plot, plus a 40m warm up section

Small scale option: Manual fell - 20m trial plot, no warm up section

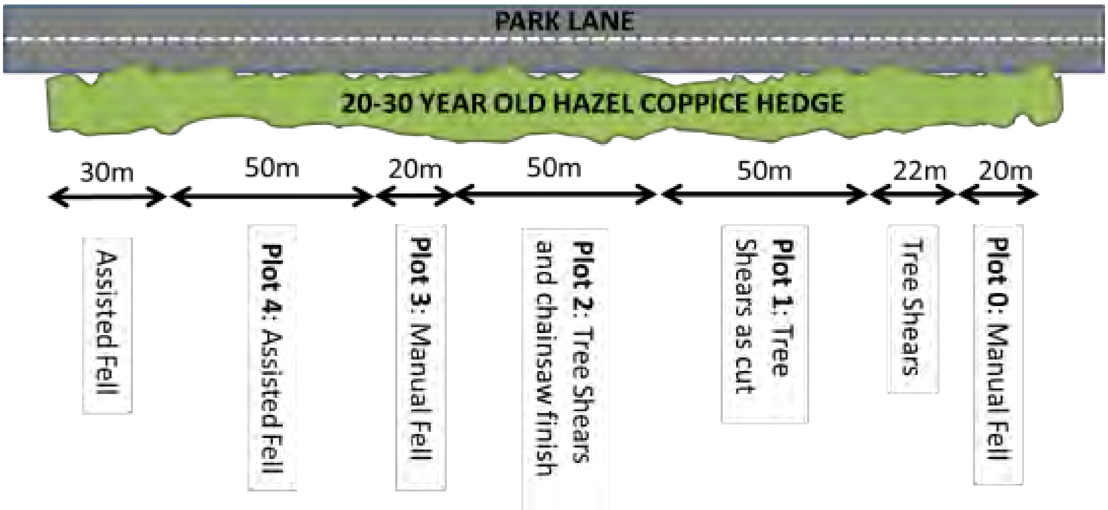

Figure 3.134. Hedgerow harvesting machinery trial plots at Hedge 21, Elm Farm

Wakelyns Agroforestry

Large scale option: Felling grapple - 40m trial plot, plus 25m warm up section

Medium scale option: Circular saw - 2 x 20m trial plots, no warm up section

Small scale option: Manual fell - 20m trial plot, no warm up section

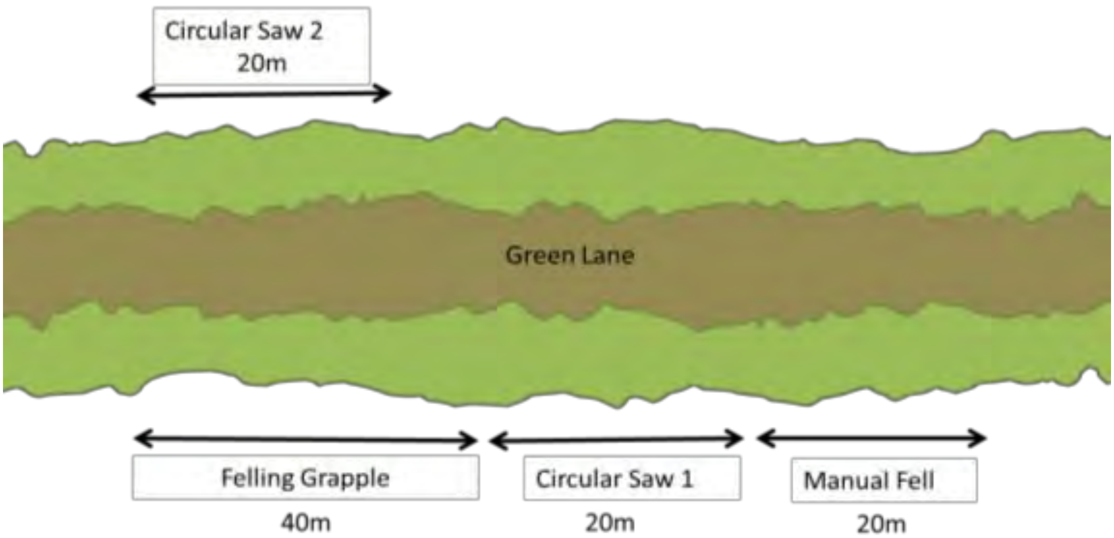

Figure 3.15. Hedgerow harvesting machinery trial plots on Hedges 1 and 2 at Wakelyns Agroforestry

3.6. Trial assessments

The trials were carried out at Elm Farm on 8-12th December 2014 and 1-10th April 2015, with coppicing carried out 8-11th December, and chipping carried out on 12th December, 1st April and 10th April. At Wakelyns Agroforestry, the trials were carried out on 24 and 25th February (coppicing) and 27th May 2015 (chipping). Both hedgerow harvesting and processing machinery was assessed qualitatively and quantitatively (Table 3.2).

Table 3.2. Hedgerow harvesting trial assessments

Parameter	Method
Qualitative assessments	
Machine availability and haulage requirements	Established when finding suitable machinery and contractors for the trials.
Ground conditions and access	On the day of the trials notes were taken on the ground conditions and access to the hedge for each machine. Any ground damage such as rutting or compaction caused by the machines and methods were also recorded and photographs taken.
Machinery operation	Researchers noted their observations on the performance and ease of operation for each machine and feedback was given by the contractors.
Quality of cut and extraction of hedgerow material	Any observations of the quality of cut for each cutting mechanism was noted and recorded and photographs taken. Ease of the extraction of hedgerow material was recorded.
Contractor and visitor feedback	Contractors were asked to give their feedback on how their machines had performed in the trial and the trials more generally. A number of people involved with hedgerow management and woodfuel production were invited to observe at both trials and asked to fill out feedback forms.
Quantitative assessments	
Hire cost and haulage cost	Quotes were provided by contactors based on the hedges used in the trials.
Capital cost	Contractors were asked how much they purchased their machinery for and whether this was second-hand or new.
Fuel use	Contractors were asked to keep a record of their fuel use throughout the day. Some contractors estimated their fuel use by starting with a full tank of fuel, recording refills during the day and refilling after the trial. Other contractors' machines were able to record their exact fuel consumption.
Coppicing and chipping time	The time taken to coppice or chip a pre-determined length of hedge or hedgerow material was recorded. Where possible the time to cut or chip each 10 metre stretch of hedge was recorded to determine variability in cutting or chipping time.
Hedgerow biomass productivity	Volume of woodchip was estimated and weight measured using a weigh load scale and a weigh bridge.
Drying, storage and woodchip quality	Samples of woodchip from each hedge were taken. Moisture content, ash content, calorific value and particle size distribution (ÖNORM and BS EN standards) were all recorded.
Coppice stool survival and regrowth	At the Elm Farm trial site the regrowth and stool survival following coppicing was monitored every two months once shoots appeared. Regrowth from each trial section was recorded to ascertain the impact of different cutting methods on stool health and regrowth.

3.7. Trial protocols and methodologies

Hedgerow harvesting protocol

The locations of the trial sections of hedge to be coppiced by each machinery option were measured, marked out and numbered prior to the start of the trials, and were allocated to the contractors on the morning of the trial.

Coppicing method: To ensure a standardised process, all contractors were given the same guidance on the morning of the trial. This stated that all hedgerow material within each trial section allotted to a contractor should be coppiced (i.e. cut once near the base of the stems), that the stems within the hedgeline should be cut leaving 2-4”/5-10cm of young wood to regrow, and that any blackthorn, bramble or other stems which have grown out from the line of the hedge should be cut to the ground, as regrowth was not required.

Marked stems: Stems were marked with red and white tape as a warning and indicated those stems not to be felled without further investigation. They either marked trees to be left as standard hedgerow trees or stems which contained a hazard, such as barbed wire which required felling with care. Orange spots were used to indicate stems to be coppiced where it was not clear or limbs of multi-stemmed trees to be removed.

Barbed wire: It was made clear to contractors that despite best efforts no guarantee could be given that no wire or metal was present in the hedge, so it was advised that care should be taken. If any were present, it was likely to be buried in the soil. It was advised that any stems with barbed wire embedded should be coppiced and the affected timber cut out, so that no metal was present in the pile of hedge material or presented to the chipper.

Removal and storage of material: To ensure that each coppicing method was directly comparable, it was required that all cut material should be removed using the machine or specified technique and placed at least 6m from the hedge with all of the butts facing the hedge and the stems perpendicular to the hedge, to enable the material to be chipped more efficiently. If material was felled manually, it should also be extracted and moved manually in order to allow for a direct comparison of harvesting methods. It was made clear that the piles of hedge material were to be kept separate for each section of hedge coppiced to enable accurate calculations of the biomass produced from each section of hedge.

Fuel use: Contractors were asked to start the trials with a full tank of fuel both for chainsaws and excavators or tractors, to note the number of times they re-filled their chainsaws with fuel, and to re-fuel their machines on site at the end of each coppice section, so we could calculate fuel use. Where this was not possible, we asked that machines be re-fuelled as soon as they returned to their yard and for contractors to let us know how much fuel they had used during the day.

Hedgerow material processing protocol

Elm Farm

For the hedge material produced from Hedge 21 at Elm Farm, the material from each coppiced section was chipped separately, and its volume and mass recorded before it was transported back to Elm Farm. All of the hedge material was due to be chipped *in situ* in the field next to the hedge on the day after the main part of the hedge coppicing trials had taken place on 11th December 2014, using a large scale crane-fed Heizohack HM 8-500 K biomass drum chipper provided by Thomson Tree Services on behalf of Wessex Biofuel.

However because of the time taken to calibrate the weigh load scales, by weighing the tractor and trailer both empty and full at a local weighbridge, and measure both the volume and mass of woodchip from each trial section, only half of the hedgerow material (113m) was chipped when green and fresh the day after coppicing on 12th December, with no possibility of the chipper returning the following day. It was therefore decided to compare the quality of the woodchip produced from the same source material but with two different types of chipper, and so a small scale disc chipper was hired to complete the chipping of the hedgerow material. The remaining half of the hedgerow material was left to dry in the field for 3.5-4 months, and was then chipped when fairly well seasoned and dry *in situ* on 1st and 10th April using a small scale manually-fed landscaper's Timberwolf TW 150 DHB disc chipper. As before it was then transported to Elm Farm.

Wakelyns Agroforestry

The coppiced hedge material from two trial sections (a 10m manual fell section and a 20m felling grapple section) was separated into cordwood and brash material in order to ascertain the impact on woodchip quality of removing varying amounts of cordwood from the hedge material. This was done by extracting the cordwood using a two person team with chainsaws. All the cordwood from a 10m section of the 20m manual fell trial plot was extracted down to 4"/10cm diameter, and from a 20m section of the 40m felling grapple trial plot the easily accessible cordwood was extracted to 4"/10cm diameter. For this 20m felling grapple section contractors were asked to extract the cordwood they thought economical in terms of firewood sale value versus labour cost, i.e. with a more commercial view on the process rather than meticulously removing all the timber to the specified diameter. The mass of cordwood from each coppiced section was weighed and recorded three months after coppicing (on 28th May 2015), and the moisture content of the cordwood was taken with an electronic moisture meter.

The remaining brash from each of these trial sections and the whole-tree hedgerow material from the other trial sections was all chipped on one day three months after it was coppiced on 27th May 2015 using a large scale crane-fed biomass drum chipper. The woodchip was chipped into a small grain trailer with extended sides and transported to a concrete yard to be loaded into the woodchip store for the on-farm woodfuel boiler. As at Elm Farm, the volume of woodchip from each trial section was estimated in the trailer and weighed using calibrated weigh load scales, and samples of woodchip were taken for quality analysis.

Hedgerow material storage and drying protocol

At the Elm Farm trials, both batches of freshly chipped (green) woodchip and the four month air-dried (seasoned) woodchip was tipped onto the swept clean concrete floor of an open-ended Dutch barn to be stored and dried. This barn had no end doors and was well ventilated. Samples of woodchip were taken straight away from the woodchip pile in the barn for moisture content and woodchip quality analysis.

The two batches of woodchip chipped with different types of chipper (drum chipper and disc chipper) and after different lengths of time after coppicing (day after coppicing when green and fresh, and four months after coppicing when seasoned and dry) created a second hedgerow material storage trial, where the drying rate and decreasing moisture content of the two batches of woodchip could be monitored.

At the Wakelyns Agroforestry trial, the three month air-dried (seasoned) woodchip was tipped onto the swept clean concrete farm yard from where it was loaded into the woodchip store for the on-farm woodfuel boiler within a few days of being chipped. This woodchip store is part of an open-fronted barn which is well-ventilated.

Hedgerow biomass measurement methods

Woodchip

Both the volume and mass of woodchip produced from each trial section of hedge were measured and summed to calculate the total biomass harvested from each hedge, and when divided by the length of the trial section or the whole hedge, gave an indication of the average biomass productivity per metre for each trial section and each hedge. This enabled harvesting time to be calculated not only on a per metre of hedge basis, but also on a per cubic metre of hedgerow material (woodchip) basis.

The volume of woodchip produced from each trial section was estimated in the trailer used to transport it, having calculated the volume of the trailer and marked the volume at $2m^3$ intervals up the inside of the trailer using gaffer tape, with the top of the tape indicating the next $2m^3$. The woodchip had to be levelled as best as possible with rakes, forks and shovels at the end of each trial section to get a good estimate of the volume. When woodchip is delivered into the Hampshire Woodfuel Co-operative woodfuel hub, the volume is calculated in the same way, so this seems to be a standardised methodology.

The mass of woodchip produced from each trial section was recorded using calibrated weigh load scales, which measure hydraulic pressure in the ram which lifts the trailer. These were borrowed from Mike Davies from Newton Lodge Farms where they are used annually to record the mass of each load of grain in a trailer. They are fitted between the tractor and the hydraulic pipe, and so can easily be connected to take a reading after each trial section. For each trailer, a standardised height was set to lift the trailer to so that all readings were directly comparable. The trailer was lifted to approximately 45cm.

The weigh load scales had to be calibrated for each trailer used; two at Elm Farm and one at Wakelyns. In order to calibrate the weigh load scales, the mass of the trailer when empty and when full of woodchip was required. For the Elm Farm trials this was done by weighing the tractor and trailer at a local weighbridge near Kintbury belonging to Hills Waste Solutions. At Wakelyns Agroforestry, there was no weighbridge nearby, so instead weigh load scale readings were taken when the trailer was empty save an empty $1m^3$ water container, and again when the water container was full, i.e. when the trailer load was 1 tonne. Weigh load scale (WLS) readings were then converted into masses using the calibration factor:

mass of trailer when full = WLS reading when full

mass of trailer when empty = WLS reading when empty

full weight /full WLS reading = conversion factor

(trial section WLS reading - empty WLS reading) x conversion factor = actual weight (tonnes)

Cordwood

Where cordwood was extracted from a trial section to be processed into firewood logs, the mass of cordwood was ascertained by weighing bundles of logs suspended from a front-mounted fork on a tractor using two rope slings (Figure 3.16). A digital spring balance recorded the mass of each bundle, and the mass of the bundles from each trial section was summed to ascertain the total mass of cordwood extracted from each of the two trial sections. This is a tried and tested method designed by Paul Ward of PJ & MJ Ward Contracting for use when calculating the biomass harvested from short rotation coppice trials at Wakelyns Agroforestry.

Figure 3.146. Weighing the hedgerow cordwood extracted from Hedge 1 at Wakelyns Agroforestry

Woodchip quality analysis methods

Sampling design

Fresh samples of woodchip were taken from each pile soon after chipping for woodchip quality analysis. Woodchip is highly variable in size and moisture content and is prone to fractionation and stratification. A large number of samples are required in order to establish sampling precision and for results to be representative of the whole woodchip pile being sampled.

For the larger woodchip piles produced from Hedge 21 at Elm Farm, a composite sampling method was chosen where samples of approximately three litres (one full bucket) were taken from ten evenly spaced locations across the pile in order to provide representative woodchip sampling. As fractionation and stratification was likely to have occurred within these stationary piles, the 10 samples were taken at varying depths. For smaller piles, such as those produced from Hedges 1 and 2 at Wakelyns Agroforestry, a composite sampling method was also used although samples were taken from a number of evenly spaced locations across the pile until approximately eight litres of woodchip had been collected.

Samples from each individual woodchip pile were then thoroughly mixed to form a composite sample that was then reduced down to the required laboratory sample sizes for each test. Woodchip samples were then clearly labelled and sealed in plastic sacks until sent off for woodchip quality analysis.

Moisture content

The moisture content of woodchip is specified as the percentage of the total weight of the sample and was determined using a simple oven drying method, where 10 sub-samples of approximately 500g were taken from each woodchip pile and then weighed (green weight) and dried in an oven at 100 degrees Celsius until a constant mass was reached (dry weight). The moisture content was then calculated by subtracting the dry weight from the green weight to calculate the weight of water. The weight of water was then divided by the green weight to calculate the moisture content of each sample.

Particle size distribution

While woodchip boiler systems can be designed to burn a variety of woodchip sizes, most are designed to work at high efficiencies requiring woodchip of the correct size, with a low proportion of fine material which would reduce the combustion efficiency and a low proportion of large shards which could jam the feed system.

Woodchip samples were tested to both BS EN 303-5 and ÖNORM M7 133 standards for particle size distribution. These woodfuel standards have become the accepted measures in the European biomass industry. Samples were tested by Woodsure (www.woodsure.co.uk), an organisation providing an accreditation scheme for assuring the quality and suitability of woodchip, wood pellets, briquettes, logs and hog fuel and who test woodfuel to both BS EN and ÖNORM standards. The methods for testing particle size distribution are detailed within the two standards and involve sieving oven dried samples of 6-8 litres through different sized sieves to determine the percentage of woodchip of certain dimensions.

Ash content

Ash is the non-combustible mineral content of woodchip and consists of oxides of alkaline earth metals, such as potassium, calcium and magnesium. The ash content of different woodchip can vary considerably depending on the bark content, bark having a higher ash content than heartwood. Although some boilers can cope with high ash content fuels, some cannot or may require adjustment to their de-ashing systems. High ash content may result in the formation of lumps of clinker or slag which can block air flow through the grate. Woodchip samples of approximately one litre were sent to the BioComposites Centre at Bangor University and their ash content determined. Ash content of the material was determined by ashing sub-samples in a muffle oven. The ash content was determined gravimetrically based on the weight remaining after combustion.

Calorific content

The calorific content of woodchip is the energy content of the fuel. While provision of the calorific content of woodchip is not an essential requirement of most standards (i.e. it is informative rather than normative), it may be a useful parameter in the comparison of woodchip produced from hedges to commercially produced woodchip from forestry cordwood. Woodchip samples were sent to the BioComposites Centre at Bangor University and their calorific content determined. Each one litre woodchip sample was milled to a fine powder using a Glen Creston mill. The powder was dried overnight and then combusted and analysed using a Parr 6100 bomb calorimeter. The results were reported in MJ/Kg.

4. Qualitative Results

4.1. Machinery availability and haulage requirements

The machinery selected and hired to take part in the trials was based ultimately on a combination of the selection criteria: a range of size of machinery and the associated range in hire costs, a range of cutting and chipping mechanisms, and the availability of machines and contractors within a workable distance of the trial sites. It had been hoped that a large-scale timber harvesting head with integral circular saw and a multi-bladed circular saw would be trialled, but because these machines are so uncommon and specialist, and the contractors therefore so busy this was not possible. Despite considerable research and ringing around, only three Bracke felling heads were found in the country, and none were available or responded to our enquiry. One contractor was amenable to being involved, but it was not economically viable to pull a machine with a Bracke felling head off a job, spend a day transporting it to the trial site and a day taking it back for only one day's work as part of the trial. This is one of the limiting factors of running a small-scale trial with a number of machinery options, as compared to hiring a single machine to carry out a substantial quantity of hedgerow coppicing work.

The tree shears, felling grapple and assisted fell harvesting methods all used excavators, which usually need to be transported on a low loader. However as the Englefield Estate contractors who carried out the assisted fell harvesting had their own lorry, this was considerably cheaper than hiring one on the open market. Both the tree shears and the felling grapple had to hire a low loader for the day, which waited whilst the trial hedge was coppiced so that a full days' hire was charged. The manual fellers arrived on site in their 4WD work truck, which was sufficient to transport their chainsaws, PPE (personal protective equipment), chainsaw fuel and tools, which was another advantage of manual felling.

4.2. Ground conditions and access

On the day of the trials notes were taken on the ground conditions and access to the hedges for each machine. Any ground damage such as rutting or compaction caused by the machines and methods were also recorded and photographs taken. Harvesting methods using large excavators, such as the tree shears and assisted fell methods, need good ground conditions to operate in order to support the 8-20 tonne excavator, with concern about compaction and rutting of grazing or arable land when the ground is wet. By contrast, hedges can be manually felled with a chainsaw in most ground conditions, except when the ground is too slippy from mud or ice to be safe, and with little compaction or rutting even when the ground is wet and soft. Pretty much all sites and hedges can be accessed by a man with a chainsaw, including where there is no vehicle access or where ground is too steep or wet.

4.3. Harvesting machinery operation

This is a qualitative analysis of the performance of each machine and each different type of cutting mechanism based on coppicing hedgerows during the ORC trials. No comment can be made on how these machines perform when felling trees in a forestry context.

Hydraulic tree shears

Dymax hydraulic tree shears provide the flexibility to choose an appropriate size of excavator and tree shears (10-14"/250-350mm) based on the size of the material to be coppiced and ground conditions. They have the flexibility to coppice a range of shrubs and trees on most sites and hedges, but have limited manoeuvrability to coppice thin multi-stemmed material, rounded coppice stools, or where the ground is uneven or sloping such as hedge banks. These Dymax tree shears are able to fell or coppice small and large diameter stems up to 14"/350mm, but are more suited (and probably actually designed) to felling larger single stems and lines of small trees. Cutting small stems one at a time or in small groups was hard work, slow, repetitive and tiring for the operator. The feller-buncher mechanism seemed to be of little help. Tree shears in general are by their nature more robust against stones and metal, such as old fencing wire which may be encountered when coppicing hedges, than saw chains which can be thrown when they catch a stone or even when cutting wood on occasion, and are prone to damage by metal objects with potentially very expensive consequences.

Felling grapple

The Gierkink felling grapple can be mounted on any size excavator from 5.5 tonnes upwards (as long as it has the correct hydraulics) depending on ground conditions, access to site and reach required. Although the felling grapple looks like it has a very loose joint (wrist) where it is mounted to the excavator, it actually has surprisingly good control enabling controlled felling and lowering down of felled trees. This felling head had good manoeuvrability, and could be used in a variety of situations and for a range of stem diameter. However, at times the felling grapple also seemed to be difficult or slow to manoeuvre into tight or awkward spaces and to cut and extract the stems, especially within and between multi-stemmed trees or coppice stems or on sloping ground, but also when cutting stems low down to the base of the stool. Like the tree shears, it is probably designed for larger single-stemmed trees rather than scrub, brushwood or coppice material. It wasn't clear whether this difficulty in manoeuvrability and slower rate of cutting was down to operator experience, the operator being a machinery dealer rather than a full-time machine operator.

Circular saw

A single circular saw on a hedgecutting arm makes use of common and relatively inexpensive agricultural machinery. The circular saw also known as a shaping saw has the flexibility to side up or brash up a hedge prior to coppicing, and to fell tall stems in sections. The circular saw is optimally designed for cutting small diameter hedgerow coppice or SRC (short rotation coppice), and is used annually for this purpose at Wakelyns Agroforestry. The single circular saw cutting diameter is limited to approximately 10"/250mm and the height of hedgerow material it can cope with is limited to 5m approximately because of poor directional control of falling material, and concerns about material falling onto the tractor cab.

The circular saw carried out further preparation of one of the circular saw trial sections where the hedge was approximately 7m tall, by siding up the hedge cutting it back so the stems were clearly visible. Cutting tall stems in sections gets around this problem, but decreases stem length and therefore ease of processing when using a crane-fed chipper. Stems larger than 10”/250mm in diameter needed to be felled manually with a chainsaw. The coppiced hedge material also needed to be cleared up and moved into a stack because it just lands where it falls. This is most easily done with a second tractor with a front-mounted fork, although some material still needs to be cleared by hand, so this is a two machine, two man felling operation.

Assisted fell

The assisted fell technique or motor manual (chainsaw) with excavator has the flexibility to work on most sites and hedges, and pretty much all sizes of timber material. Like the tree shears, it provides the flexibility to choose the appropriate size excavator based on the size of the material to be coppiced and ground conditions. The excellent manoeuvrability of a manual feller and chainsaw allows a huge range of timber diameters to be cut, from thin multi-stemmed coppice stools on hedgebanks to large single-stemmed trees, and in a site-specific manner and with a good clean cut. This is a very quick and effective felling method, making best use of both manual and mechanised felling techniques, with the excavator able to take the brunt of the physical work in extracting and moving the hedgerow material as full length stems ready for quick and easy processing. A tractor with front-mounted fork or grab could just as easily be used instead of an excavator.

This coppicing method demands a very experienced team who are used to working together, due to the intimate nature of the working methodology. There are health and safety concerns with regards to the manual feller working near or under the excavator arm when the machine is running. Englefield Estate commonly use this felling method and have completed a risk assessment of it which they consider satisfactory.

Manual fell

The motor manual method of coppicing using a man and a chainsaw is also incredibly flexible, and allows for coppicing work to be carried out on most sites and hedges with pretty much any size of timber material. The chainsaw allows for a site-specific approach to be taken, can accommodate the contours of coppice stools or hedgebanks, and has the manoeuvrability to cut multi-stemmed trees and handle any proximity and density of stems and stools. Where smaller trees or coppice stems are being felled, manual felling using a bowsaw or hand saw could be used instead of a chainsaw. However this kind of work is only done manually where dedicated individuals or large teams of volunteers are involved and available to do the work.

The main limitation of manual felling is the size of timber which can be manually extracted and moved without an excavator to assist, and the slow rate of work. The physical strength limitation and personal safe lifting limit means cordwood needs to be cut into shorter lengths, which makes handling them for firewood processing or chipping and particularly with a crane-fed chipper more difficult and much slower. The personal safe lifting limit can easily be exceeded, especially if there are single-stemmed trees present in the hedge. Where the material is multi-stemmed and stems are tall, they need holding by one person whilst the other cuts, and can be very hard and slow to extract from the tangled canopy. A pole with a hook on the end was used by one set of contractors to assist this process, but this manual felling method is not suitable where there are large single-stemmed trees, or where the hedge is more than approximately 5m tall. The feller's reach is much more limited than that of a more mechanised method, for example across a stream or to make high-level cuts, without expensive tree climbing. A significant amount of time is required for re-fuelling and saw sharpening during each day when using a chainsaw. The rate of hedgerow coppicing appeared to be dependent on the mean diameter of the hedgerow material, the proportion of large diameter trees, and also seemingly the quantity of work to be done.

Ease of operation

Researchers noted their observations on the ease of operation for each machine and feedback was given by the contractors. For the tree shears and felling grapple, the ease of using these machines to coppice hedges may well depend on operator experience, and particularly experience of felling and handling small diameter and multi-stemmed material. The circular saw and manual fell methods worked best and were easier on small diameter coppice material which was less than 5m tall, and both struggled where the hedge was taller and there were larger single-stemmed trees. The circular saw method needed the larger trees to be felled manually, and the manual fell method struggled to handle larger diameter cordwood and extract tall brushwood without the assistance of a machine. The assisted fell method worked well whatever the diameter of timber and coppiced the hedge with ease, although it did require an intimate working methodology, with some health and safety concerns.

Quality of coppice cut

Observations on the quality of cut for each cutting mechanism were noted and recorded and photographs were taken.

Hydraulic tree shears

The Dymax tree shears were clearly designed to cut or harvest single-stemmed trees and not small diameter multi-stemmed shrubs, as they resulted in some stems being cut very high because of the difficulty getting between stems on a multi-stemmed coppice stool and cutting low down to the stool. Some stems were left with untidy rough cuts with splinters and some deep splits down stems into the stool (Figure 4.1). Two of the three sections were finished with a chainsaw (long and short finishes) to tidy them up and remove the worst of the splits; however this required a chainsaw operator to do this work. Some small stems ended up being uprooted rather than cut through, although most of these were blackthorn outgrowth which was not required to regrow so wasn't a problem, but it nonetheless highlighted the limitations of this machine.

Figure 4.1. Hazel coppice stool cut by tree shears showing rough cuts and splits

Felling grapple

Figure 4.2. Hedge coppiced by felling grapple, but thin stems left

The felling grapple with integral chainsaw could cut stems cleanly, but the finish was variable because the angle of cut was limited to a greater or lesser extent. The felling grapple head was very manoeuvrable, and so the angle of the chainsaw could be altered but it still struggled to get between stems on a multi-stemmed stool, and to cut stems on sloping ground. It seemed difficult for it to cut very small stems, predominantly because the grab couldn't hold them securely whilst they were being cut, with the result that some were pulled out of the ground.

Circular saw

The circular saw was much more limited in the angle at which it could cut, and therefore all the stems in one stool or in one section of hedge were all cut at the same height and angle, rather than being able to follow the contours of a coppice stool. The cut was less clean than a chainsaw blade resulting in a lot of splinters around the edges of larger stems in particular. Split stems can be tidied up with a chainsaw, but this requires a chainsaw operator to be present and available. The untidy rough cuts and splits down stems give some concern regarding disease ingress and regrowth.

Figure 4.3. Multi-stemmed trees and stools cut by circular saw at Wakelyns Agroforestry

Chainsaw

Coppicing carried out with a chainsaw resulted in good clean cuts which were generally angled away from the centre of the stool so water would shed off the stool rather than pool in the middle and cause rot. So both manual fell and assisted fell harvesting methods were equally good in this respect.

Figure 4.4. Multi-stemmed field maple tree cut by chainsaw at Elm Farm

Extraction of hedgerow material

All of the coppicing methods extracted the hedgerow material and stacked it as requested 8m from the hedgeline and perpendicular to the hedge with the butts of the cut stems facing the hedge ready to be fed straight into the chipper, but some did it more thoroughly and neatly than others.

Hydraulic tree shears

The tree shears removed most of the material from the hedgerow, but quite a lot of stems were cut higher than 12”/300mm or were split, so small offcuts were generated from tidying up these stems with a chainsaw which could not easily be collected, harvested and chipped, plus some brambles and thin blackthorn stems were left in the hedge. Although not all of the biomass was extracted, the resulting pile of hedgerow material had less brambles and dead twigs in it and no earth, which may have resulted in cleaner woodchip being produced. The pile of material was not stacked so neatly because it was more difficult to place it using the tree shears.

Felling grapple

The felling grapple left the hedge and the stack of coppiced hedgerow material in a similar condition to the tree shears, with some brambles, dead twigs and thin stems being left in the hedge, although the stems were not tidied up or shortened with a chainsaw because they were generally not split.

Circular saw

The circular saw resulted in a similar amount of material being harvested and extracted from the hedge as the felling grapple, but the large diameter cordwood was extracted in short lengths and stacked separately from the brushwood. The brashy hedge material was heaped up away from the hedge, but the stems were not stacked neatly or lined up with their butts facing the hedge, because of the random manner in which the material fell and was then cleared up with a front-mounted tractor fork.

Assisted fell

For the assisted fell method, the hedgerow material was easily removed from the hedge, maximising the biomass harvest, and the hedgerow material was very neatly stacked ready for chipping. However, the land rake used to extract the material combed the hedge base very neatly, extracting brambles and dead twigs and possibly some soil, which although it left a very tidy coppiced hedge, probably had a negative effect on the woodchip quality.

Manual fell

The manual fell method removed all the hedgerow material from the hedge, with every stem being cut and extracted, maximising the biomass harvest. For the hazel coppice and blackthorn hedge at Elm Farm, the hedgerow material was very neatly stacked away from and perpendicular to the hedge. However for the hedge at Wakelyns Agroforestry, which contained quite a few 35-45 year old single and multi-stemmed field maple trees, the large diameter cordwood was extracted in short lengths and stacked separately from the brushwood.

4.4. Processing machinery operation

This is a qualitative analysis based on the performance of each machine when processing the whole-tree hedgerow material generated during the ORC trials. No comment can be made on how these machines perform when chipping whole single-stemmed trees or virgin roundwood in a forestry context.

Ease of operation

Crane-fed Heizohack HM 8-500 K biomass drum chipper

This chipper used for the Elm Farm trial is a very fast and effective chipper, processing the whole hedge material at 15m^3/hr chipping time (not including for the time required to take measurements). The crane feed system allowed for large bundles of whole-tree hedgerow material to be fed into the chipper very quickly and with ease. The brashy high volume material needs to be fed into the chipper butt (base of the cut stem) first, with the material ideally having been laid out with the butts of the stems facing the chipper side feed. It is however a heavy machine, at approximately 9 tonnes, and appears to be ideally suited to use in a yard or on a track, as it caused rutting and compaction in the field on the soft though not wet ground. This chipper requires a lot of timber prepared, ready and easy to feed in order to work hard and most efficiently, and make use of its high hire cost (£100/hr). Its chipping rate equated to 280m hedgerow material per day, so at least 280m of hedge is required to make using this machine and hiring it for a day worthwhile. The more material there is to chip, the more economical the processing cost will be. Collaborating with neighbours to create large quantities of material which could be chipped at a few close sites in one day or as part of one job could make a significant difference to the cost of chipping hedgerow material.

Crane-fed Jenz HM360 fuel grade drum chipper

This chipper used for the Wakelyns Agroforestry trial performed very similarly to the Heizohack chipper, in that it was also a very fast and effective chipper, the crane-feed system worked very well, and it had a high volume chipping rate. The hedgerow material had been laid out optimally so the piles were perpendicular to the chipper, with the stem butts largely facing the chipper side feed. The Jenz chipper was a very quiet machine, even when standing quite near to it, quieter than either the Timberwolf or the Heizohack. It seemed to be a superior piece of machinery, with an automatic no-stress feed system, where the top roller and intake tray would jog into reverse when large pieces of timber were going through so as not to overload the chipping drum. It just methodically worked its way through all of the material, without any sign of stress. Whether this was down to the mechanical design of this chipper or the operator skill and experience it is hard to say, but it is likely that operator skill had a significant role to play in the machine's performance. The fully controllable rotating brash grab mounted on the telescopic crane was very skilfully operated.

The 8.6m reach telescopic crane enabled more material to be reached without having to move the chipper and cause further ground disturbance or compaction (see Figure 3.12). The extra wide 600mm flotation tyres reduced its ground pressure and impact on soft or sensitive sites, as demonstrated by the fact that there was no sign of compaction in the field at Wakelyns Agroforestry, despite the chipper and crane weighing approximately 11 tonnes. However, the chipping was done at Wakelyns Agroforestry at the very end of May whereas it was done in mid-December at Elm Farm. The downside to chipping at the end of May was that the hedgerow material seemed to be drier than that chipped in December or April at Elm Farm, so that chipping produced lots of dust, especially as there was a slight breeze on the day of chipping.

Manually-fed 6" Timberwolf TW 150 DHB disc chipper

This disc chipper was used to chip the second half of the hedgerow material at Elm Farm. It is relatively easy and simple to use as chippers go, but is likely to perform best when used by an experienced operator. Being light it caused little compaction of the ground, and given that its maximum chipping diameter was only 6"/150mm it chipped the whole tree hedge material with no difficulties, although a few of the largest pieces of cordwood (15-20cm diameter) had to be sliced diagonally in two with a chainsaw in order to be able to feed them into the chipper.

Feeding the material by hand allowed for a greater scrutiny of the material being chipped, enabling root balls with earth attached to be removed, thereby improving the woodchip quality, however it was a very slow and labour-intensive process. A two man team was employed with the chipper, but it took four people working full time to keep the chipper fed and chipping for as much of the time as possible. It was especially slow because the hedgerow material was very tangled and very hard to extract by hand (Figure 4.5).

Figure 4.5. Extracting and hand feeding hedgerow material into the Timberwolf disc chipper at Elm Farm

The long thin bushy stems of the hedgerow material, with its mix of hazel, blackthorn, field maple and bramble, had become fully entwined especially having sat in a heap in the field for nearly four months. The chipping rate was further hampered by the width of the splayed intake of the chipper, so that the quantity of bushy and high volume material which could be fed into the chipper at once was limited (see Figure 3.13).

Both with regards to manually extracting timber from a heap and manually feeding the chipper, it appears that this chipper is really designed and ideally suited for small diameter single-stemmed timber, and not high volume bushy hedgerow material. The chipper spout was only 2.26m from the ground which was very low compared to the sides of the grain trailer, so the trailer back had to be open to enable the chip to be blown in. This meant it was difficult to level the chip in the trailer in order to estimate the volume. It was also an incredibly noisy chipper, and as we were working so close to it, ear defenders and ear plugs were essential.

Welmac UK branch logger

A demonstration of the branch logger proved it to be a very efficient and economical small diameter timber processing machine. With this one machine, whole trees and shrubs can be fed through, chopped up into 6"/150mm lengths, and the chunked material dropped straight into string bags ready for (garage forecourt) sale (see Figure 2.2.G). It is an incredibly quick, easy and efficient way to process whole-tree hedgerow material into a saleable product bagged and ready to sell in a one-stage process. It can also be used to process waste wood such as pallets, as long as it's nail and metal-free presumably, and other small diameter timber into a ready to sell product. This branch logger is also an easy to use machine which does not require specialist operator training, but experience is likely to ensure the smooth running of the machine and maximum efficiency of the chunking process.

Its limitations are the diameter of timber material it is able to process and the rate at which it can process bushy high volume shrub material. As with the Timberwolf chipper, the chunking rate is likely to be limited by the width of the splayed intake, limiting the quantity of high volume material which can be fed into the branch logger at once. To operate it most effectively, it requires a two man team at least; one to feed it and one to remove full bags of chunked wood and replace the string bags. How fast the bags can be swapped may also limit the throughput rate.

Another potential limitation of this machine and the inherent whole-tree chunking process is the nature of the processed material produced and its market. If whole tree material is fed into the machine, then a high proportion of very small diameter sticks and twigs will be produced as well as small logs. Some bags will predominantly contain small logs, but others may contain a large proportion of sticks and twigs. This is not likely to be an issue for the self-supplier who understands that all timber burns and even the smallest twigs make good kindling, but it may affect the saleability of the material, with customer expectations for clean kindling and logs, rather than twigs. In order to address this, the cordwood may need to be extracted from the brashy material prior to chunking, but this would add time and therefore cost to the process, and miss the opportunity to use the whole tree and prove that this is a sustainable and worthwhile thing to do.

Visual assessment of woodchip quality

Crane-fed Heizohack HM 8-500 K biomass drum chipper

Lack of operator understanding or experience of small diameter hedgerow material, or a lack of confidence in it as a suitable source material for producing woodchip meant that the intake or feed speed on the chipper was set to maximum in order to maximise the size of the chip, but this resulted in some large chips and quite a few shards. It is assumed that the 35/40mm sieve which is designed to prevent shards and splinters going through was in place, but it would seem questionable given the high number of shards and the disappointingly poor visual appearance of the woodchip.

Crane-fed Jenz HM360 fuel grade drum chipper

The operators were used to processing small diameter material, scrub and coppiced material, and so weren't phased by this hedge coppicing work, and didn't alter the intake speed. The chipper's integral 35mm sieve was in place and prevented most shards and splinters going through, resulting in good quality woodchip on visual inspection, particularly when compared to the chip produced by the Heizohack chipper, with relatively few shards, splinters or long bits of stick.

Manually-fed 6” Timberwolf disc chipper

The disc chipper produced nice clean small woodchip. Quite a lot of the woodchip was quite small (10-15mm diameter, well below 30mm diameter or G30 standard) and there were quite a few long thin little sticks because there was no sieve. However the woodchip quality on the basis of a visual assessment appeared to be better than that produced by the Heizohack.

Figure 4.6. Hedgerow woodchip produced by the Timberwolf TW 150 DHB disc chipper

4.5. Contractor and visitor feedback

Contractor feedback

Contractors were asked to give their feedback on how they felt their machines had performed in the trial and on the trials more generally. The key points are summarised below.

Tree shears operator:

- *using tree shears on small material is very difficult and slow work*
- *difficult to grab material (multiple stems)*
- *hazel stools are difficult to get the shears into*
- *the work is very tiring 'worse than a 14 hour day'*
- *need bigger material*
- *need an open hedge with little undergrowth*

Assisted fellers:

- *positive overall and found it an easy job*
- *better if people respected the road closure*
- *blackthorn difficult to get into, hazel easier to get into to cut*
- *the idea of coppicing the whole hedge is feasible and is estimated would take 2 days*
- *brash piles not as neat*
- *mulching the hedge would be easier but you wouldn't get any woodchip for woodfuel*
- *if the stems were bigger it would take more time*
- *the circular saw they own only goes on a 20 tonne excavator so would need a low loader*
- *when using a circular saw the material can fall in any direction*
- *they bought the circular saw with the intention of using it on hazel coppice*
- *this assisted fell technique is used in forestry*
- *chainsaw is likely to be best for very large trees as felling heads are limited to certain sizes*

- *they used a root fork on the excavator which did a clean tidy job and worked well with the stools*
- *they have their own design of fork for larger trees/jobs*
- *on other jobs they either leave brash or burn it*
- *they use their circular saw at Pamber Forest for Englefield Estate*
- *the 2 man father and son assisted fell team have worked together for 30 years (now being 44 and 72 years old)*

Manual fellers:

- *overall very positive about the job and considered it to be an easy and 'nice' job*
- *having to move brash 6m out from the hedge by hand slowed them down*
- *blackthorn easier and quicker to take out as smaller and on the field side*
- *hazel took longer to take out as required more handling (one man to hold and one to cut)*
- *if the hazel coppice was larger there might be a difficulty if the road wasn't closed; they would have to use stop-go signs*
- *confident they could coppice the whole 250m hedge, though it would take ca. 4 days*

Visitor feedback

Rupert Brown of John Brown & Sons, famers in Suffolk said after attending the hedgerow harvesting trials at Wakelyns Agroforestry, "We are looking at how to manage hedgerows which have grown out of control. We may have found a solution. We await the results of the research into the cost of differing methods [of hedgerow coppicing] being published."

In anticipation of visiting the hedgerow harvesting trials at Wakelyns Agroforestry, Harry Jennings wrote "Combining the right technology, (from hedge to grate) with long-term hedge management plans, and authentication of sustainability, is just what I'm looking for."

5. Quantitative results

5.1. Hire and purchase cost

Harvesting machinery

Fig. 5.1 shows both the daily cost of hire with and without haulage for each harvesting machinery option trialled. The larger scale machinery options (hydraulic tree shears and felling grapple) were found to be the most expensive options and had similar costs to each other both with and without haulage. The medium scale machinery options (circular saw and assisted fell) had slightly lower hire costs than the larger options when haulage was not included and almost 60% cheaper when haulage was included. The manual fell options had the lowest hire costs with and without haulage. The difference in hire costs between the two manual fell options was most likely due to use of different contractors rather than hedge type. VAT is likely to be charged by most contractors and so needs to be taken into consideration when budgeting.

For both the hydraulic tree shears and felling grapple, haulage accounted for around 50% of the day hire cost. These larger scale machinery options are likely to require haulage involving the use of a low-loader for most jobs. Despite the felling grapple having to be transported 128 miles to Wakelyns Agroforestry and the hydraulic tree shears only having to be transported 50 miles to Elm Farm, the haulage cost was the same for both options (£500). This haulage cost was therefore taken to be the cost of hiring a low-loader for a day and appears not to be based on distance travelled.

The haulage costs of options which do not require the use of a low-loader (all machinery options except the hydraulic tree shears and felling grapple) are more likely to be based on distance. However, in most situations these other smaller scale machinery options are likely to be available from more locally based contractors. In both trials local contractors were used to provide the medium and small scale machinery options. The haulage costs quoted for these options are therefore presumed to be what most people can expect to pay. For all harvesting options the hire cost including haulage has been used for all further economic analysis within this report.

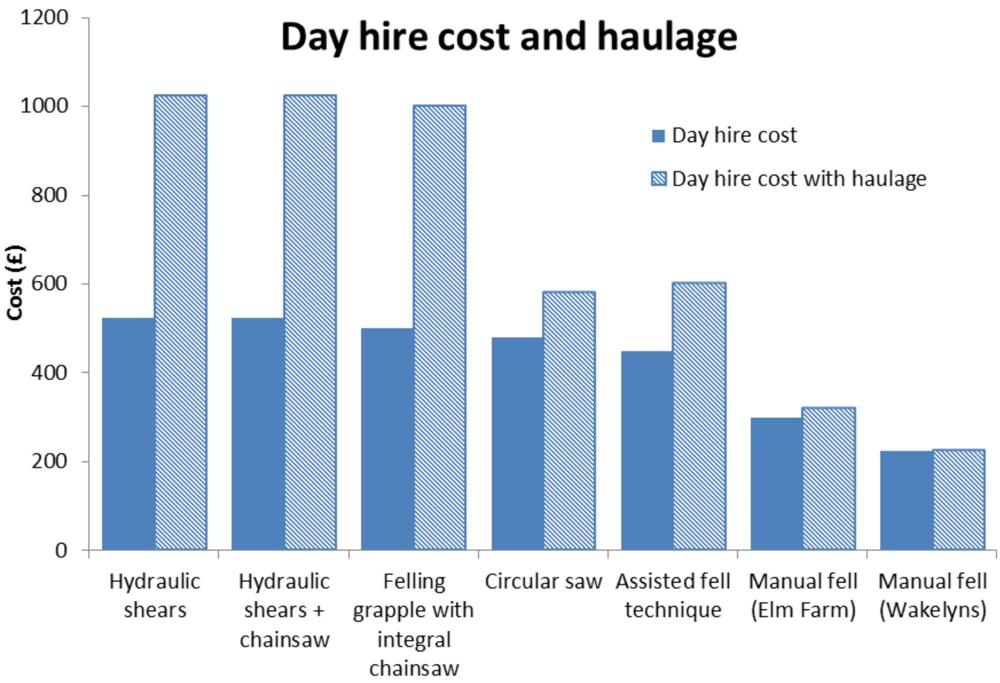

Figure 5.1. Day hire cost with and without haulage of harvesting machinery trialled (costs exclude VAT)

A summary of the results can be found in Appendix 1.

Figure 5.2. Purchase cost of the harvesting machinery trialled when new, excluding and including the cost of a base vehicle (excavator or tractor assumed to be £40,000) based on figures given by contractors (costs exclude VAT)

The hydraulic tree shears, felling grapple and the circular saw were found to be the three most expensive options in regards to new purchase cost, both with and without the additional cost of a base vehicle, excavator or tractor (Figure 5.2). When the cost of a base vehicle is included, these three options and the assisted fell technique are substantially more expensive than the manual fell option. All new machinery will incur VAT and so needs to be taken into consideration when budgeting.

Processing machinery

The larger scale chipping options (Heizohack and Jenz drum chippers) were found to be more expensive than the small-scale chipper (Timberwolf) in terms of both hire cost and purchase cost (Figure 5.3 and Figure 5.4). Although a haulage cost was only given for the Heizohack chipper, it is expected haulage of both the Jenz and Timberwolf chippers was included in the hire cost as a standard cost. Despite the Heizohack and Jenz chippers having similar specifications their hire costs differ. This may be due to the differing day rates of different contractors, as with the two manual felling contractors, or the higher purchase cost of the Heizohack chipper.

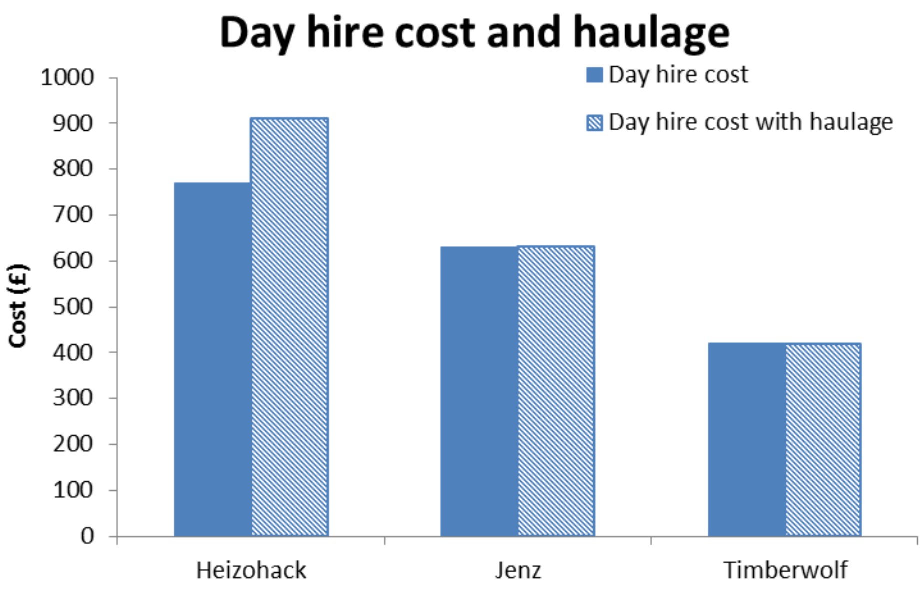

Figure 5.3. Day hire cost with and without haulage of chippers trialled (costs exclude VAT)

These hire costs do not include the hire of a tractor, operator and 11 tonne grain trailer for moving woodchip from field to barn, which would be approximately £350/day based on figures given by the contractors and the John Nix Farm Management Pocketbook 2014.

Figure 5.4. Purchase cost when new of the three chippers trialled based on figures given by contractors (costs exclude VAT)

5.2. Fuel use

The fuel use of each harvesting and processing method was estimated by each contractor. Fuel costs were however included in the hire cost of all of the machinery options trialled. At Wakelyns Agroforestry the felling grapple used the most fuel per metre at 0.5 litres/m followed by the circular saw (0.43 litres/m); this may be due to both these options being used on Hedge 1 which contained large diameter material requiring extra handling and had a higher volume of hedge material per metre to harvest (Figure 5.5 and Figure 5.13). The hydraulic tree shears and assisted fell had similar fuel usage, as did both manual fell options. Fuel use was similar among the three chippers trialled (Fig. 5.6). The Heizohack drum chipper used the most fuel per metre (0.63 litres/m) followed by the Jenz drum chipper (0.5 litres/m) and then the Timberwolf disc chipper (0.45 litres/m).

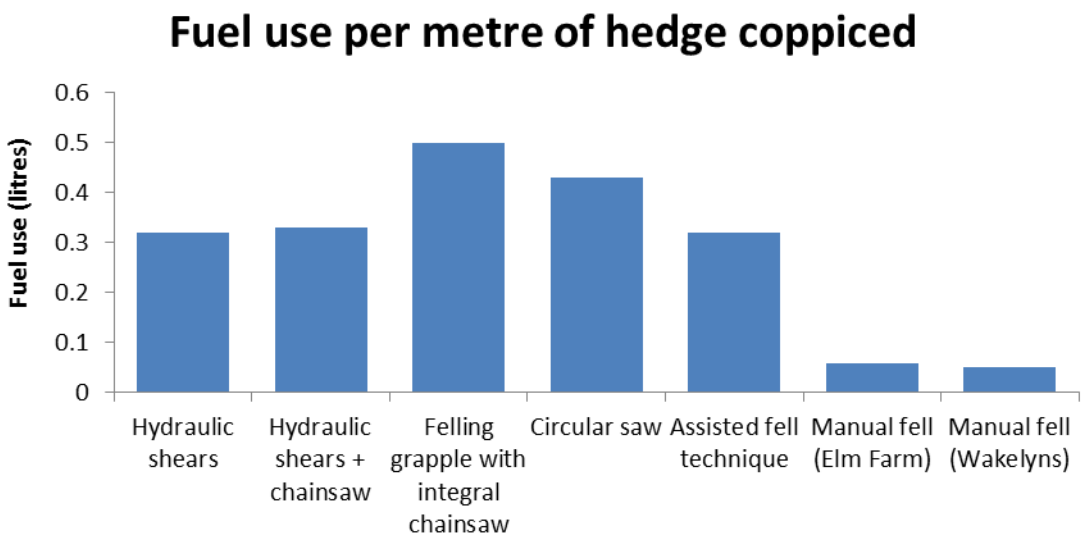

Figure 5.5. Average fuel use in litres per metre of hedge coppiced for the harvesting machinery trialled

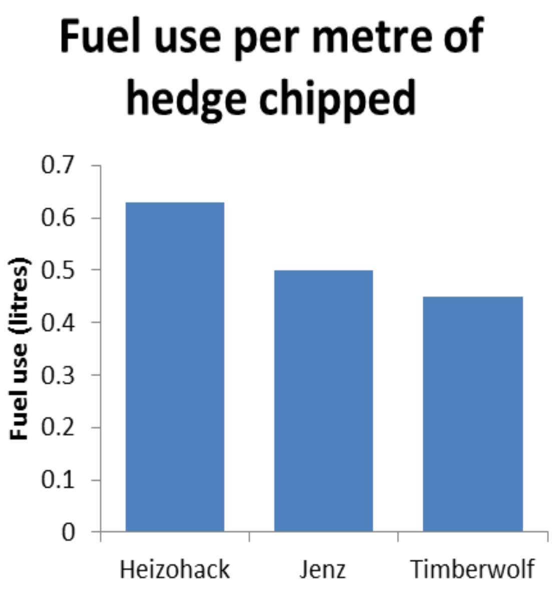

Figure 5.6. Average fuel use in litres per metre of hedge material chipped for the three chippers trialled

5.3. Maximum efficiencies

Maximum efficiency refers to the maximum length of hedge each machine can harvest or process in an eight hour working day: one hour given for lunch and breaks and seven hours of cutting or chipping time. The maximum efficiency was calculated from the average time taken for each machine to coppice or chip a set length of hedge or hedge material.

Harvesting machinery

The assisted fell method was found to be the quickest harvesting method used on Hedge 21 at Elm Farm, able to cut 266m in one day (Figure 5.7). At a maximum efficiency of 159m of hedge per day the felling grapple was the fastest harvesting option trialled on the hedges at Wakelyns Agroforestry. Despite being trialled on hedges of different character, both the felling grapple and hydraulic tree shears had simular maximium efficiencies, 159m and 151m respectively. For both the manual fell and circular saw options, maximum efficiency was shown to vary with hedge type; both options were most effective on the thinner hedges with a lower diameter, volume and biomass of material to harvest (Hedges 2 and 21), suggesting these options are better suited to material of a small diameter.

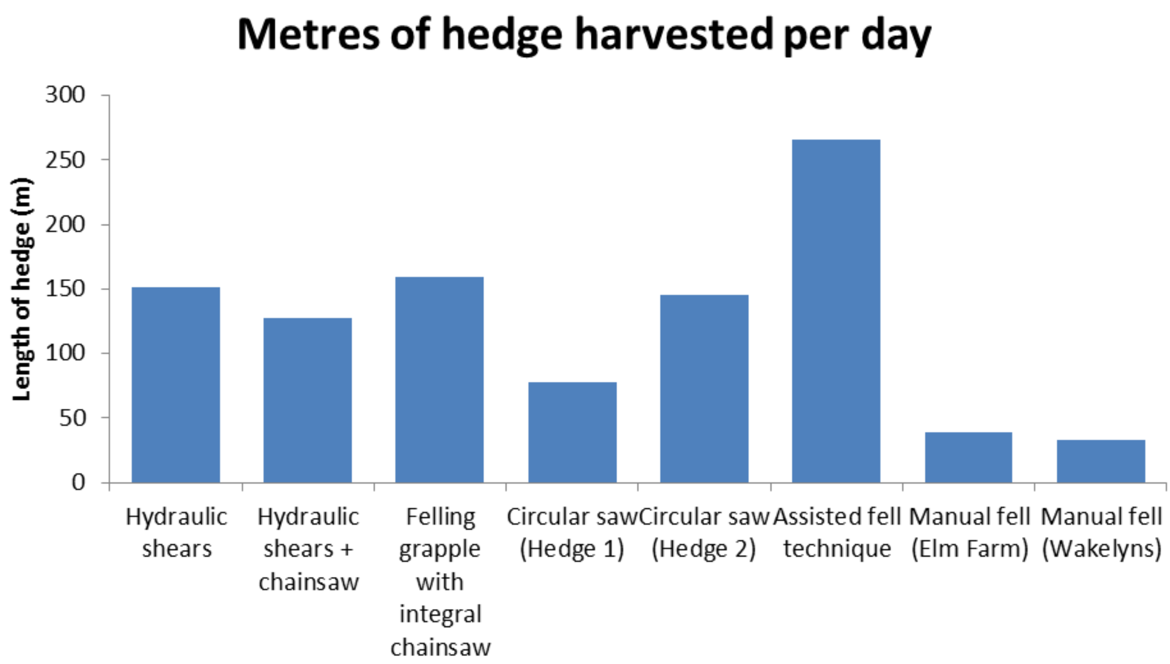

Figure 5.7. The maximum efficiency in metres of hedge harvested per day for the harvesting machinery trialled

Processing machinery

Despite being trialled on different hedge types which varied considerably in the volume of hedgerow material they produced (see Figure 5.13), the larger drum chippers had similar chipping efficiencies (Figure 5.8). The Heizohack drum chipper had the highest efficiency at 284m of hedge material chipped per day followed by the Jenz drum chipper at 258m. This difference could be due to a number of factors such as the chipping throughput rate of the machines themselves, their operators and the type of hedge material. Both of the larger chippers had higher maximum efficiencies than the small Timberwolf disc chipper (84m).

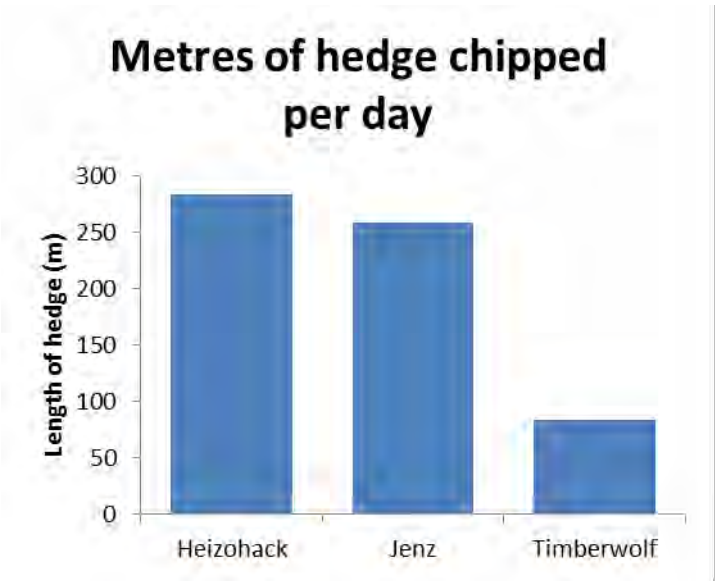

Figure 5.8. The maximum efficiency in metres of hedge material chipped per day for the three chippers trialled

5.4. Harvesting and processing costs

The harvesting and processing costs are given per metre of hedge, as shown in Figure 5.9 and Figure 5.10, and have been calculated by dividing the day hire cost by how many metres each machine could harvest or chip in a day. This is based on an eight hour working day: one hour given for lunch and breaks and seven hours of cutting or chipping time. At Elm Farm the assisted fell (£2.26/m) was significantly cheaper than both the hydraulic tree shear options (£8.06/m and £6.78/mn with and without the chainsaw finish respectively) and the manual fell (£6.85/m). At Wakelyns Agroforestry the timber grab was found to be the cheapest option (£6.28/m), followed by the circular saw (£7.46/m) and manual fell (£8.24/m). The Timberwolf disc chipper had the highest cost per metre of the three chippers (£5.01/m) followed by the Heizohack (£3.21/m) and Jenz chippers (£2.44/m).

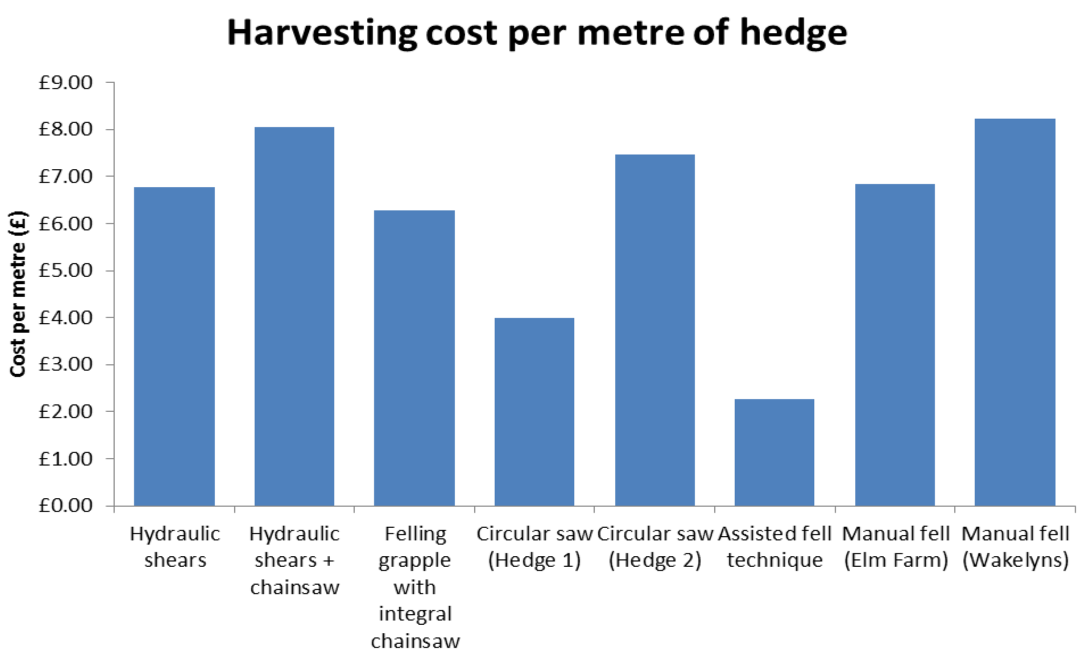

Figure 5.9. Harvesting cost per metre of hedge for each harvesting machine trialled. Costs are based on each machine being used at their maximum efficiency per day

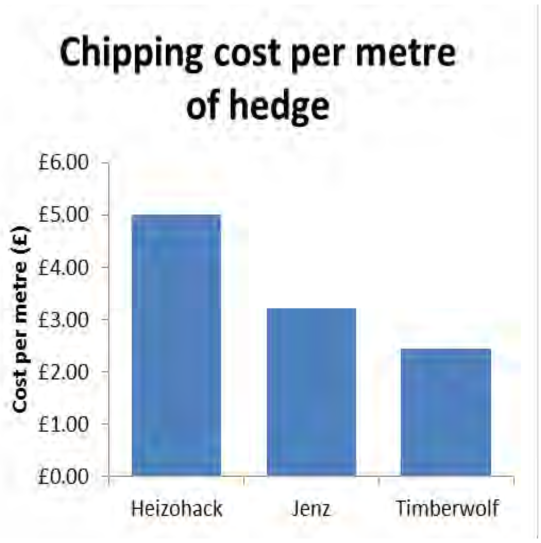

Figure 5.10. Chipping cost per metre of hedge for the chippers trialled. Costs are based on each machine being used at their maximum efficiency per day

The harvesting and chipping cost per metre will however vary depending on the length of hedge coppiced. For example, if you hire a large and expensive chipper capable of chipping 250m of hedge material in a day and you only have 50m of hedge, the cost per metre will be higher than if you coppiced sufficient length of hedge to keep the chipper working all day. As you increase the length of hedge to be chipped and approach each chippers' maximum efficiency, the cost per metre decreases as shown in Figure 5.11, where the chipper options have been used as an example.

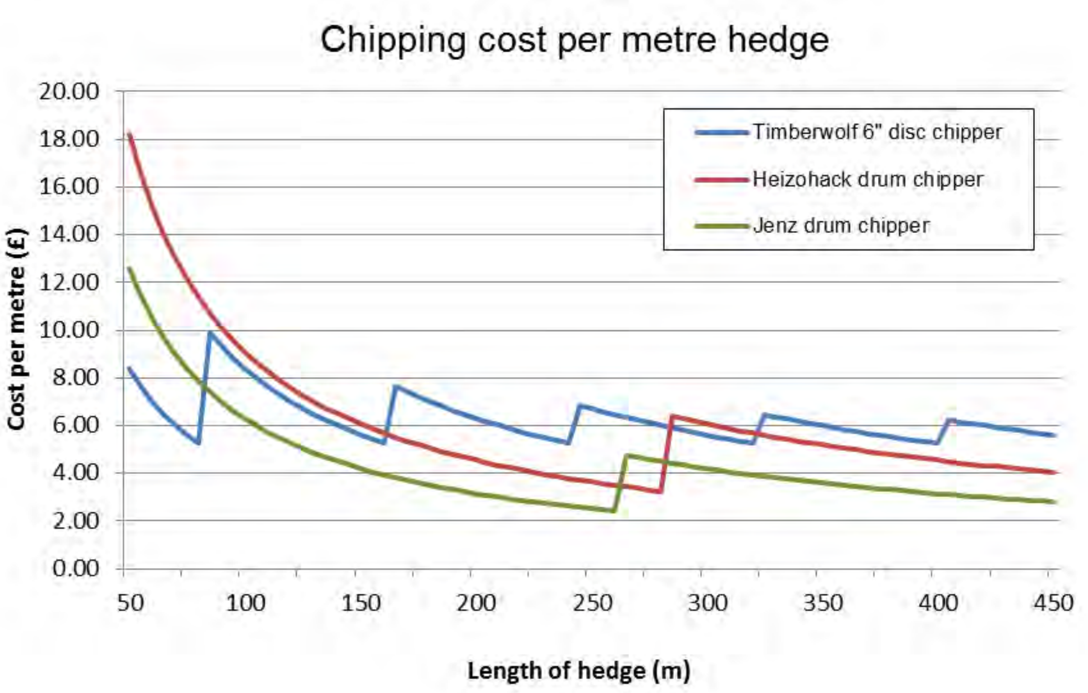

Figure 5.11. The variation in chipping cost per metre of hedge material as the length of hedge increases. This is given as an example of how the (harvesting or chipping) cost per metre decreases with hedge length as the maximum efficiency is approached. Note that the cost per metre increases sharply after the hedge length exceeds the machine's maximum efficiency, due to the machine needing to be hired for a whole extra day for only a small amount of material

However, if you were to chip over 250m of hedge you would need to hire the machine for an extra day to coppice the remaining material. This would result in the cost per metre increasing once again. These spikes in the chipping cost per metre seen in Figure 5.11 are however unlikely to occur in practice as it would be uneconomical to hire a machine for a whole extra day to chip only a small amount of extra material. Figure 5.12 therefore shows the decrease in cost per metre with hedge length when these spikes are normalised. For all of the harvesting and chipping methods trialled the lowest cost per metre is reached when the hedge length to be coppiced and chipped approaches and equals that of the machines' maximum efficiency in a day.

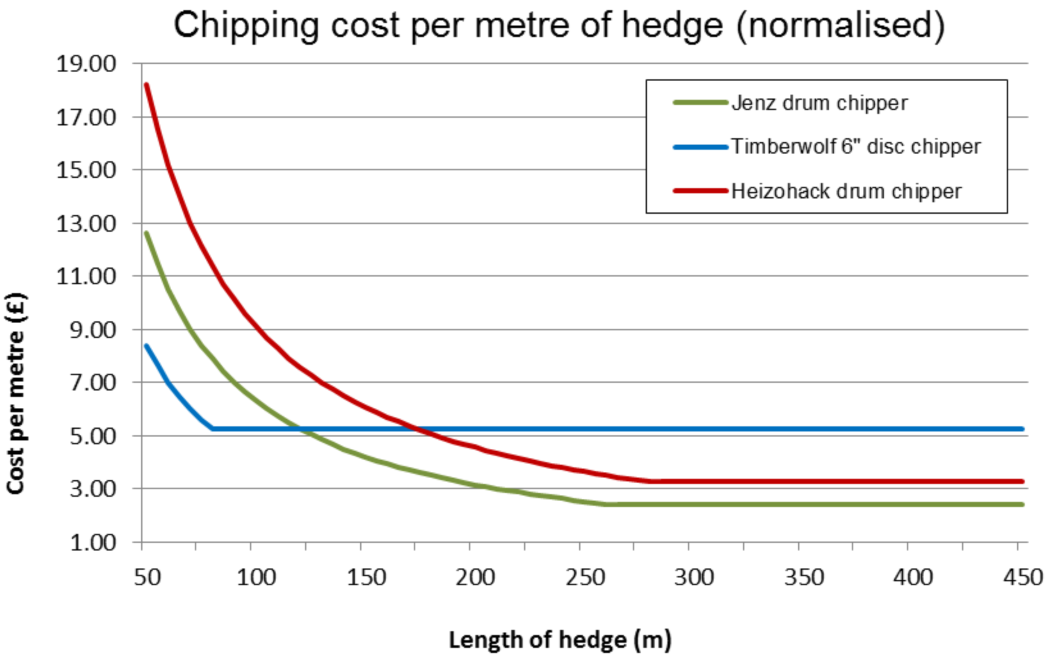

Figure 5.12. The decrease in chipping cost per metre of hedge material as the length of hedge increases, shown when the spikes seen in Figure 5.11 are normalised. These decreasing cots per metre are based on the assumption that a machine will be used at is maximum efficiency, ie will work hard all day for each day it is hired to maximise the cost effectiveness of hiring it

5.5. Biomass productivity

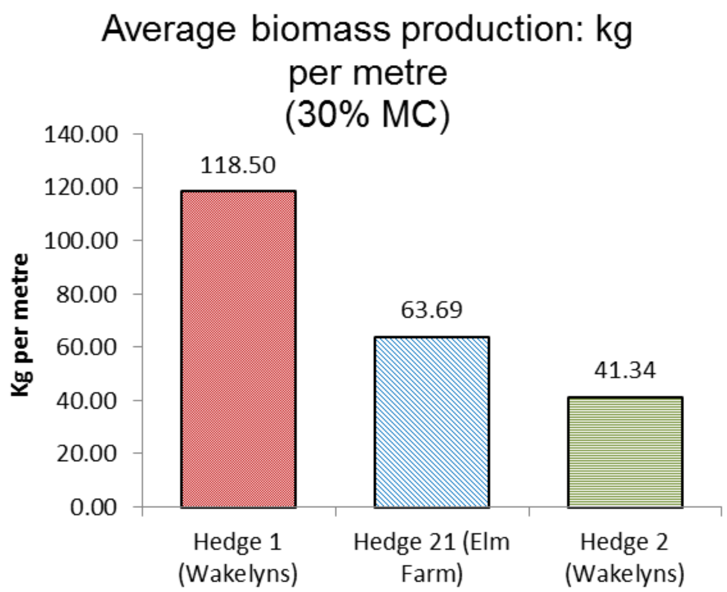

Figure 5.13. Average hedgerow biomass productivity in kg per metre (at 30% MC) for the three hedges coppiced in the trials

The mass of woodchip harvested from each trial section was measured using a weigh load scale on the woodchip trailer, summed to give the total biomass harvested from each hedge, and divided by the length of the hedge to give the average biomass productivity per metre, as described in 3.7 Hedgerow biomass measurement methods. Hedge 1 was shown to have to highest productivity producing 118.5 kg per metre of hedge, followed by Hedge 21 (63.69 kg/m) and Hedge 2 (41.34kg/m) as shown in Figure 5.13.

At Wakelyns Agroforestry cordwood was extracted from the hedge material coppiced from two of the trial sections, as described in 3.7 Hedgerow material processing protocol, in order to be processed into saleable firewood. The 10m section where cordwood was extracted down to 10cm/4" in diameter was more productive in terms of overall biomass and cordwood production; cordwood made up 63.05% of the biomass extracted (Figure 5.14). In the 20m section where the easily accessible and economical cordwood over 10cm/4" was extracted, cordwood made up 58.38% of the total biomass extracted.

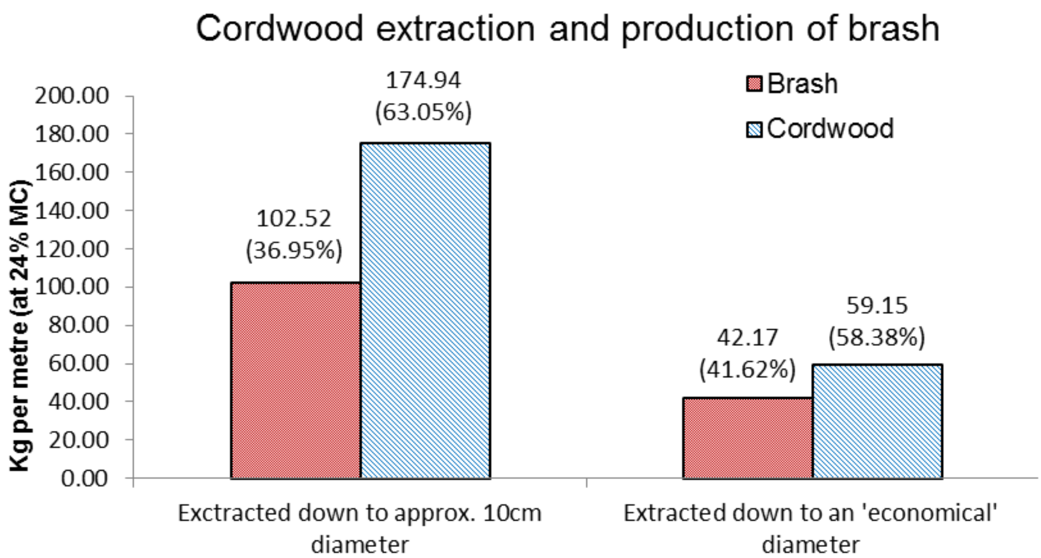

Figure 5.14. Extraction of cordwood from coppiced whole-tree hedgerow material from two trial sections of Hedge 1 at Wakelyns Agroforestry, and the resulting proportion of brash:cordwood

5.6. Woodchip quality results

Calorific content

The woodchip quality results (Appendix 2) indicate that the more cordwood that is extracted the lower the calorific content of the woodchip produced (Figure 5.15). Whole-tree woodchip from Hedge 1 had a calorific content of 19.41 MJ/kg, while woodchip produced from the brash after cordwood extraction had a calorific content of 18.99 MJ/kg when extracted economically down to to approximately 10cm diameter, and 18.86 MJ/kg when extracted thoroughly down to 10cm diameter.

Little variation was found in the calorific content of the whole-tree woodchip produced from the three different hedges whether chipped dry or green (Figure 5.15). Woodchip produced from Hedge 1 at Wakelyns Agroforestry (predominantly field maple and hawthorn) had the highest calorific content at 19.41MJ/kg, with woodchip from Hedge 21 at Elm Farm (predominantly hazel and blackthorn) having an average calorific content of 19.20MJ/kg, and woodchip from Hedge 2 at Wakelyns Agroforestry (predominantly hazel with some field maple) having the lowest calorific content at 19.06MJ/kg.

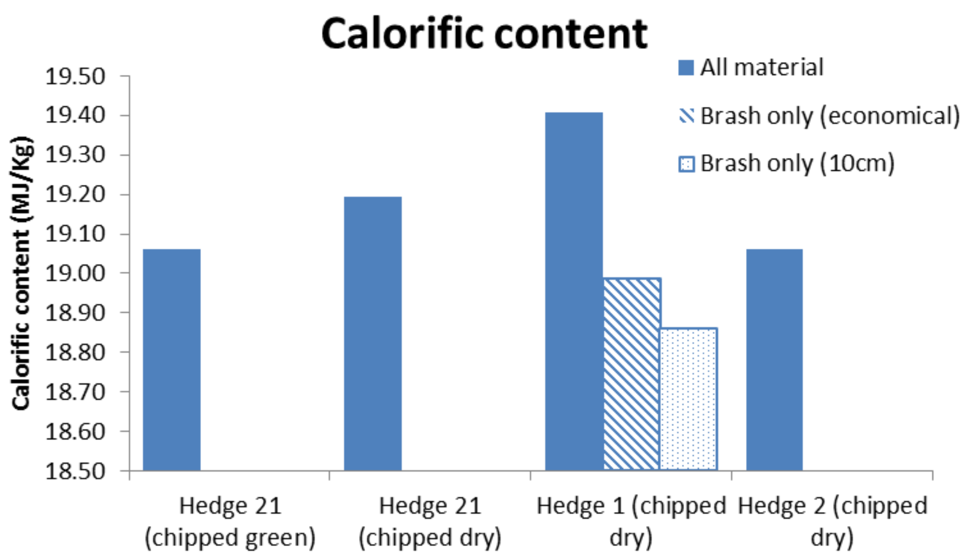

Figure 5.15. Calorific content of the hedgerow woodchip in Megajoules (MJ) per kg produced from the coppiced trial hedges

Ash content

The ash content of woodchip produced from hedge material that had been left to air-dry in the field for three months ranged from 2.06% to 2.93%, however the woodchip produced from Hedge 21 where the material was chipped green had the highest ash content at 3.58%.

The woodchip produced from Hedge 1 at Wakelyns Agroforestry, where varying proportions of cordwood were removed, showed that where the cordwood had been extracted down to 10cm the resultant woodchip produced from the remaining brash material had a higher ash content (3.83%) than the whole-tree hedgerow woodchip from Hedge 1 (2.93%) (Figure 5.16). However for the woodchip produced from the remaining brash, where the cordwood had been extracted economically, the ash content was lower (2.42%) than the whole-tree woodchip. It is not clear why this should be.

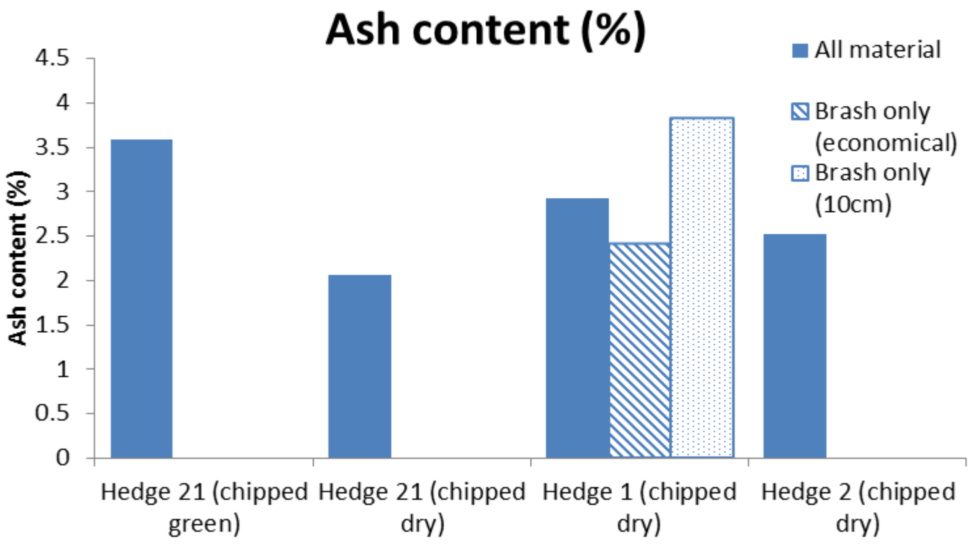

Figure 5.16. Ash content (%) of the hedgerow woodchip produced from the coppiced trial hedges

Moisture content

Woodchip produced from whole-tree hedgerow material left to air-dry in the field for three months before chipping was found to have an average moisture content of 24%, while the woodchip produced from self-dried green hedgerow material had a moisture content of 30.58% after the same period (Figure 5.17). Both the brash based hedgerow woodchip samples were of similar moisture content (23.08% and 23.57%).

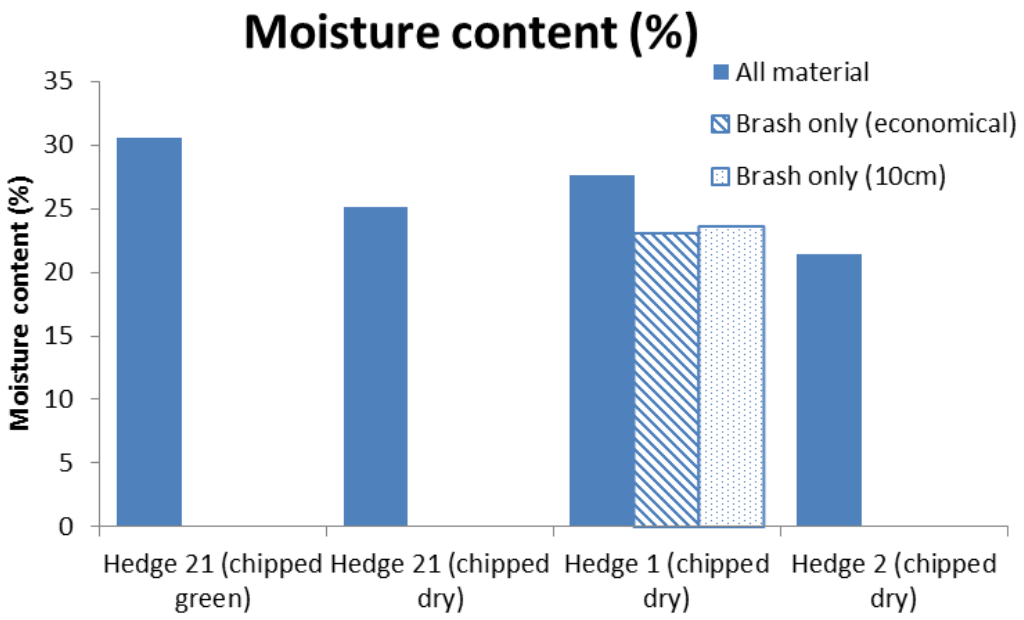

Figure 5.17. Moisture content (%) of the hedgerow woodchip produced from the coppiced trial hedges

Particle size distribution

All of the whole-tree hedgerow woodchip samples passed the BS EN standards and ÖNORM G30 standards for particle size distribution, indicating that a suitably high proportion of the hedgerow woodchip was greater than 30mm in diameter, and therefore saleable on the open woodchip market. They did all fail the ÖNORM G50 standards however, indicating the generally small nature of the hedgerow woodchip which is as expected when producing woodchip from a small diameter timber source material.

Both the brash based woodchip samples failed the BS EN standards and ÖNORM G50 standards, indicating a large percentage of finer material (<5.6mm) within the woodchip (Table 5.1 and Appendix 3). However the woodchip produced from the brash where the cordwood was extracted down to 10cm diameter did pass the ÖNORM G30 as it had a lower percentage of woodchip sized over 16mm than the other brash based chip (Appendix 3).

Table 5.1. Results of woodchip quality and particle size distribution analysis as tested against the BS EN and ÖNORM G30 and G50 standards for the samples of hedgerow woodchip produced from the trials

Woodchip	ÖNORM standards		BS EN standards
	G30	G50	P16B
Hedge 21 (chipped green)	PASS	FAIL	PASS
Hedge 21 (chipped dry)	PASS	FAIL	PASS
Hedge 1 (chipped dry)	PASS	FAIL	PASS
Hedge 2 (chipped dry)	PASS	FAIL	PASS
Hedge 1 Brash only (economical)	FAIL	FAIL	FAIL
Hedge 1 Brash only (10cm)	PASS	FAIL	FAIL

5.7. Savings from reduced hedgerow flailing

Most hedges in the UK are managed by flailing with a tractor-mounted hedge cutter. This is often carried out annually, particularly on arable farms and roadside hedges. It is estimated to cost 88p per metre (in diesel, machinery costs including wear and tear, depreciation and labour) to flail the top and sides of a 2m hedge each year (SPON's External Works and Landscape Price Book, 2014). Over 15 years this amounts to a flailing cost of £13.20 per metre. Coppicing a hedge reduces the need for regular hedge flailing to just side trimming every 3 years to control outgrowth. Table 6.2 shows the potential savings from reduced flailing as a result of coppicing compared to annual flailing over 15 years when different combinations of machinery options are used. These figures are based on a 15 year coppice rotation, where the hedge is side flailed four times over this period and assumes that all machines are used to their maximum efficiencies.

These figures therefore indicate the maximum possible savings in flailing costs under these machinery combinations. To achieve these savings in practice, each option would need to be used at its maximum efficiency which may require hedge material being stored until enough material has been accumulated to keep the larger chippers working hard for a full day.

Table 5.2. Potential flailing savings per metre from coppicing compared to flailing annually over 15 years given for the different harvesting and chipping machinery options trialled

	Chippers		
Harvesting machinery	**Heizohack**	**Jenz**	**Timberwolf**
Hydraulic shears	-£0.31		-£2.12
Hydraulic shears with chainsaw	-£1.59		-£3.39
Felling grapple with integral chainsaw		£0.95	
Circular saw (Hedge 1)		-£0.22	
Circular saw (Hedge 2)		£3.23	
Assisted fell	£4.22		£2.41
Manual fell	-£0.38	-£1.00	-£2.18

For Hedge 21 at Elm Farm a saving is only made when the assisted fell option is used with either the Heizohack drum chipper (£4.22/m) or the Timberwolf disc chipper (£2.41/m). All other combinations trialled at Elm Farm do not incur a saving, costing between £0.31 and £3.39 more per metre than flailing annually. For Hedge 1 at Wakelyns Agroforestry only the felling grapple used with the Jenz drum chipper made a saving, which was £0.95/m. The circular saw and manual fell machinery options cost £0.22 and £1.00 per metre more than annual flailing respectively. On Hedge 2 at Wakelyns Agroforestry the circular saw made a saving of £3.23 per metre.

It is important to note that these savings or costs only refer to the potential to reduce flailing costs by coppicing, and do not take into account the value of the product produced i.e. the woodchip which can either be used on-farm or sold locally.

5.8. Profit from sale of hedgerow woodchip

Potential buyers for the hedgerow woodchip produced as a result of the Elm Farm hedgerow harvesting trial were found locally and asked to provide quotes. Figure 5.18 shows the prices offered per tonne of woodchip at 30% moisture content (MC). The cost of delivery to the local buyers was estimated to be £16.60 per tonne. The net prices offered per tonne when these transport costs are taken into account are also shown in Figure 5.18.

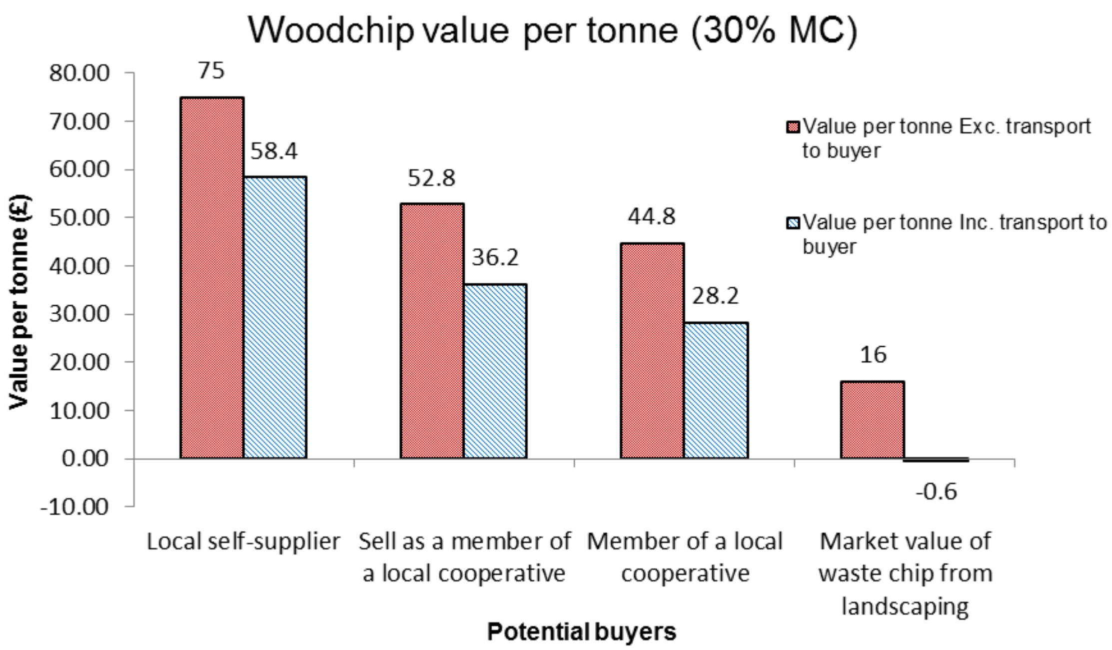

Figure 5.18. Price per tonne offered by potential local buyers for hedgerow woodchip produced from the Elm Farm trial. The net price per tonne offered when transport costs (£16.60 per tonne) have been deducted are also shown

Having taken into account the harvesting (coppicing) and chipping costs of producing hedgerow woodchip (which includes the cost of transporting it to the storage barn but doesn't include storage costs), Table 5.3 shows the potential profit per tonne (at 30% MC) once the hedgerow woodchip has been sold, assuming the highest offered woodchip price of £75 per tonne (excluding transport to buyer costs).

Table 5.3. Profit per tonne of hedgerow woodchip when sold at £75/tonne (excluding transport to buyer) at 30% MC

	Chippers		
Harvesting machinery	Heizohack	Jenz	Timberwolf
Hydraulic shears	-£81.85		-£110.20
Hydraulic shears with chainsaw	-£101.93		-£130.28
Felling grapple with integral chainsaw		£1.34	
Circular saw (Hedge 1)		-£8.55	
Circular saw (Hedge 2)		-£81.01	
Assisted fell	-£10.77		-£39.12
Manual fell	-£82.93		-£111.28

The only harvesting and chipping machinery combination where an overall profit of £1.34/tonne is made, is the felling grapple and the Jenz drum chipper used on Hedge 1 at Wakelyns Agroforestry. All the other machinery combinations result in a net loss per tonne of hedgerow woodchip produced. However this analysis is only based on the market price which can be achieved for the woodchip and not its energetic or financial value as a fossil fuel substitute, the cost implications of which are discussed in 5.9 and 5.10.

5.9. Profit from sale of hedgerow woodchip with flailing savings

Table 5.4 shows the potential profit per tonne of hedgerow woodchip achieved through reduced hedgerow flailing costs plus the income received when the woodchip is sold at £75 per tonne (or £18.75/m³ at 30% MC excluding transport to buyer costs). When the sale value of the hedgerow woodchip was offset against the hedgerow woodchip production costs (coppicing and chipping costs), together with the savings from reduced flailing costs, a net profit was achieved for two of the machinery combinations. The felling grapple and Jenz chipper machinery combination (on Hedge 1 at Wakelyns Agroforestry) achieved a net profit of £9.35/tonne, and the assisted fell and Heizohack chipper combination (on Hedge 21 at Elm Farm) made a net profit of £55.49/tonne. However this does mean that a net loss was made for all of the other machinery combinations trialled.

A few other machinery combinations were also close to break even, with the assisted fell and Timberwolf chipper combination (on Hedge 21 at Elm Farm) making a small loss of £1.28/tonne, reflecting the lower efficiency and higher processing cost of the smaller chipper. The circular saw and Jenz chipper (on Hedge 2 at Wakelyns Agroforestry) resulted in a small loss of £2.87/tonne, while the circular saw and Jenz chipper on Hedge 1 at Wakelyns Agroforestry made a loss of £10.41/tonne. The difference here illustrates the greater efficiency and therefore lower harvesting cost of the circular saw on the smaller diameter hazel coppice material of Hedge 2.

		Chippers	
Harvesting machinery	Heizohack	Jenz	Timberwolf
Hydraulic tree shears	-£86.72		-£143.48
Hydraulic tree shears with chainsaw finish	-£126.90		-£183.50
Felling grapple with integral chainsaw		£9.35	
Circular saw (Hedge 1)		-£10.41	
Circular saw (Hedge 2)		-£2.87	
Assisted fell	£55.49		-£1.28
Manual fell	-£88.90	-£23.56	-£145.51

Table 5.4. Savings per tonne of hedgerow woodchip (30% MC) after woodchip sold at £75/tonne

Looking at the machinery combinations and the hedge types which proved to be the most profitable, it can be seen that it was where the harvesting method best matched the size and volume of hedge material to be coppiced that hedgerow coppicing proved to be most profitable. It is also true that the harvesting cost was lowest where the diameter and volume of hedge material was lowest, but in terms of net profit this would be offset by a lower income received from a smaller volume of woodchip.

As expected, these figures give a more positive picture compared to Table 5.3, as further savings from reduced flailing costs have been taken into account. However it is very encouraging to show that when the full production costs are taken into account, the sale of hedgerow woodchip can break even or even generate a small profit, and if the energetic value of the woodchip is offset against the cost of other fuels, the cost savings are even greater, as discussed in 5.11.
It should be noted however that the figures presented in Table 5.4 are based on using each machine at its' maximum efficiency, and on a generous market value of £75/tonne or £18.75/ m³, where the second highest offer was £52.80/tonne or £13.20/m³. These figures therefore present the most favourable and profitable scenario. To achieve these savings in practice, each option would need to

be used at its maximum efficiency which may require hedge material being stored until enough material has been accumulated to keep the larger chippers working hard for a full day.

Figure 5.19 shows the profit or savings from the sale of hedgerow woodchip after flailing savings for two machinery combinations, 1) assisted fell and Heizohack chipper and 2) manual fell and Timberwolf chipper, when used on Hedge 21 at Elm Farm. It illustrates that it makes economic sense to use machinery with a maximum efficiency close to the length of hedge you wish to coppice. For example, if you have under 150m of hedge it is best to use a small-scale machinery option such as the manual fell and Timberwolf chipper and for hedges over 150m it is better to use the assisted fell with the Heizohack chipper.

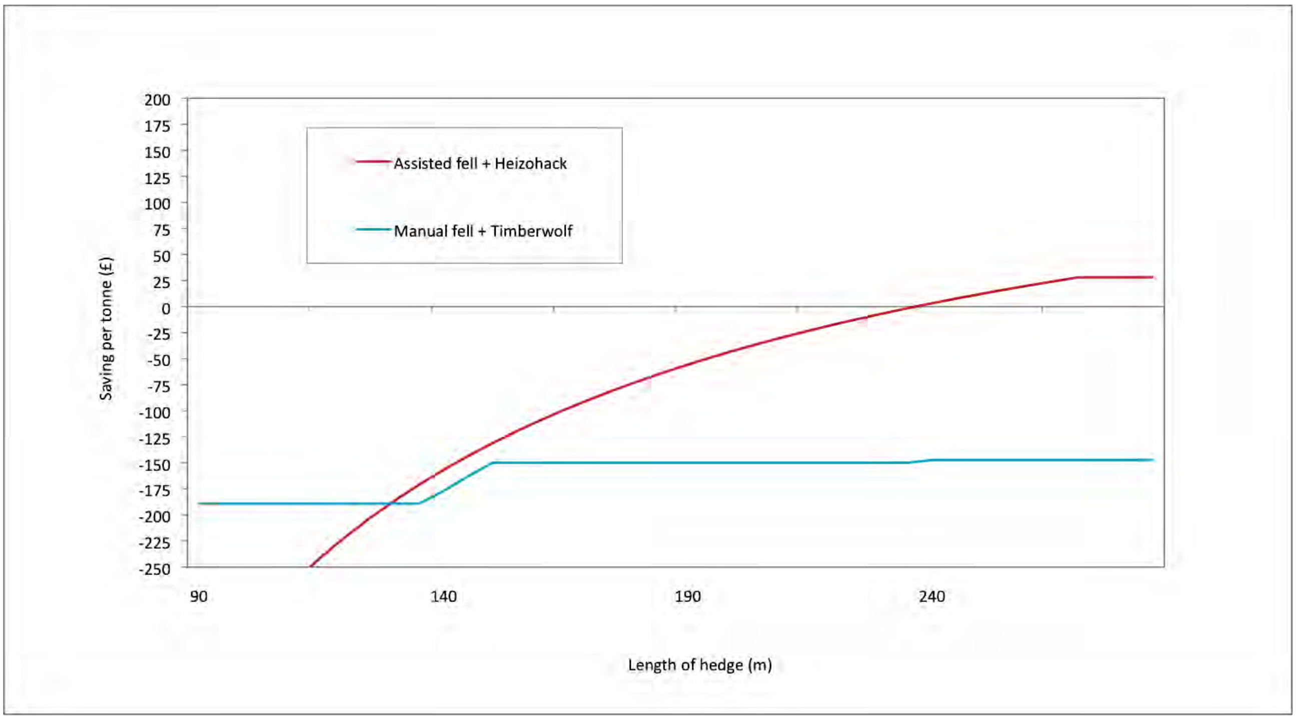

Figure 5.19. A comparison between the savings or profit per tonne of hedgerow woodchip sold when produced using 1) assisted fell and Heizohack chipper combination and 2) manual fell and Timberwolf chipper combination to illustrate the importance of choosing the right machinery options for the scale of hedgerow harvesting work to be carried out

5.10. Unit energy cost of hedgerow woodchip

The unit energy cost refers to the production cost of a unit of energy (one kilowatt-hour) for hedgerow woodchip when produced using different machinery combinations. This is calculated by dividing the cost of producing one tonne of woodchip by how many potential kilowatt-hours (kWh) that tonne can produce. The number of kWh contained within a tonne of woodchip was determined by converting the calorific content (MJ/kg) of the woodchip produced by each of the three hedges into kWh.

Table 5.5. The production cost per unit of energy (£/kWh) for hedgerow woodchip produced using the harvesting and processing machinery combinations trialled

	Chippers		
Harvesting machinery	Heizohack	Jenz	Timberwolf
Hydraulic shears	£0.029		£0.035
Hydraulic shears with chainsaw	£0.033		£0.039
Felling grapple with integral chainsaw		£0.014	
Circular saw (Hedge 1)		£0.015	
Circular saw (Hedge 2)		£0.029	
Assisted fell	£0.016		£0.021
Manual fell	£0.030	£0.017	£0.035

These production costs per unit of energy are based on the harvesting (coppicing) and chipping costs of producing hedgerow woodchip but don't include storage costs. Once again these costs per unit of energy shown in Table 5.5 are only achievable when all machines are used at their maximum efficiencies. These therefore represent the lowest production cost per unit of energy (kWh) possible for these machinery combinations based on our data.

For Hedge 21 at Elm Farm, the assisted fell and Heizohack drum chipper combination realised the lowest cost per unit of energy at 1.6 pence/kWh, followed by the assisted fell and Timberwolf disc chipper (2.1 pence/kWh). The hydraulic tree shears with chainsaw finish and Timberwolf chipper had the highest cost per kilowatt-hour at 3.9 pence/kWh, followed by the hydraulic tree shears with chainsaw finish and Heizohack chipper (3.3 pence/kWh). Both manual fell and the hydraulic tree shears had a similar cost per kilowatt-hour regardless of which chipper was used (between 2.9 and 3.5 pence/kWh). At Wakelyns Agroforestry the lowest cost per kilowatt-hour was realised using the felling grapple and Jenz drum chipper (1.4 pence/kWh), followed closely by the circular saw and Jenz chipper on Hedge 1 (1.5 pence/kWh) and manual fell and Jenz chipper (1.7 pence/kWh).

5.11. Annual energy cost and comparison with other fuels

To bring these energy unit costs into context, the annual energy cost for three types of building were calculated based on the energy unit cost (pence/kWh) of other fuel types and woodchip produced from Hedge 21 at Elm Farm as shown in Figure 5.20. The energy unit costs shown in Figure 5.20 are "input" prices, i.e. the cost of the fuel before the inefficiency of the boiler is taken into account in order to allow for a like-for-like comparison. Wood fuel boilers are typically 85-90% efficient (Forest Fuel, 2015).

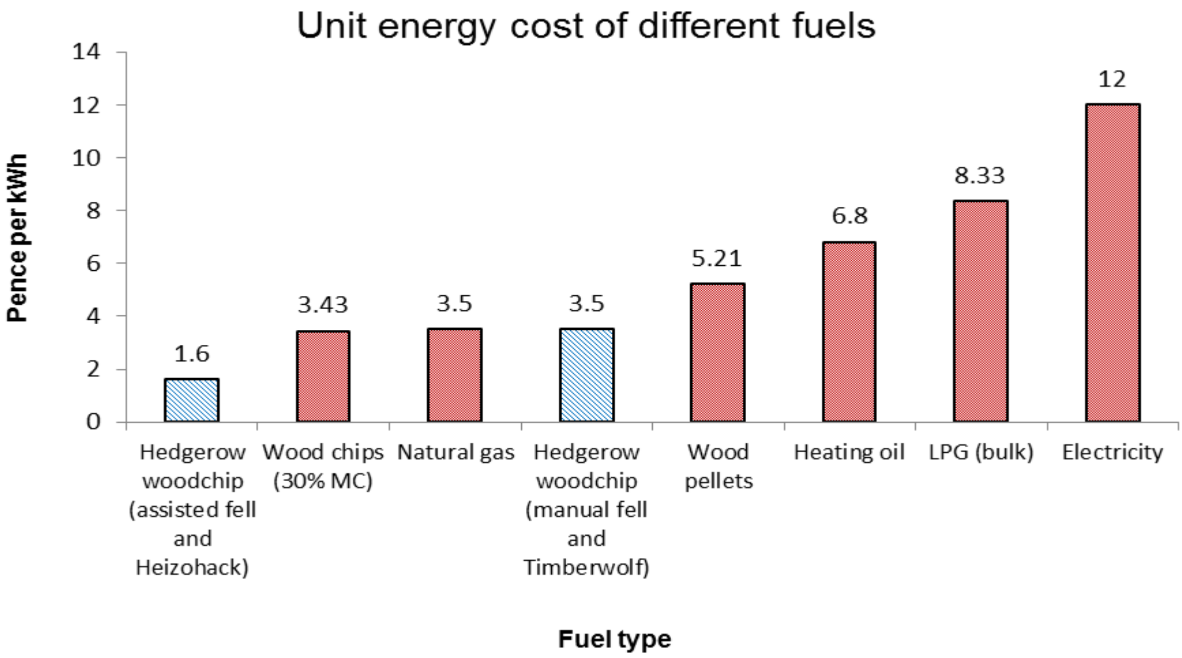

Figure 5.20. The unit energy cost of hedgerow woodchip produced from Hedge 21 at Elm Farm using 1) assisted fell and Heizohack chipper and 2) manual fell and Timberwolf chipper alongside the unit energy costs for other fuel types (from 2014 and sourced from Forest Fuels 2015). Woodchips (30%MC) refers to woodchip produced from forestry roundwood

The energy cost of hedgerow woodchip, which ranged from 1.6 to 3.5 pence per kWh depending on machinery options and hedge type, would seem relatively favourable when compared to the cost of commercially produced woodchip from forestry roundwood (3.43p/kWh), natural gas (3.5p/kWh), wood pellets (5.21p/kWh), heating oil (6.8p/kWh), LPG (8.33p/kWh), and electricity (12p/kWh) (Forest Fuels, 2015).

As shown in Table 5.6, substantially less hedge is needed to produce enough woodchip to meet the annual energy demands of a domestic house compared to both the small industrial unit and large farm with outbuildings. The annual energy cost of the domestic house was therefore calculated (for both Table 5.6 and Figure 5.21) assuming the smaller scale manual fell and Timberwolf disc chipper machinery combination was used, as these options are better suited to shorter lengths of hedge and will give the cheapest cost per unit of energy. For both the small industrial unit and large farm with outbuildings the annual energy cost was calculated assuming the large scale assisted fell and Heizohack drum chipper machinery combination was used.

Table 5.6. Estimated annual energy consumption of different building types and the required mass of woodchip and length of hedge required to meet this demand. Data on building energy consumption was sourced from the Biomass Energy Centre (2014)

Building	Annual energy consumption (kWh)	Tonnes per year (30% MC)	Metres of hedge per year	Annual energy cost using hedge woodchip
Domestic house	20000	3.75	59	£700
Small industrial unit	140000	26.26	412	£2,240
Large farm with outbuildings	400000	75.04	1178	£6,400

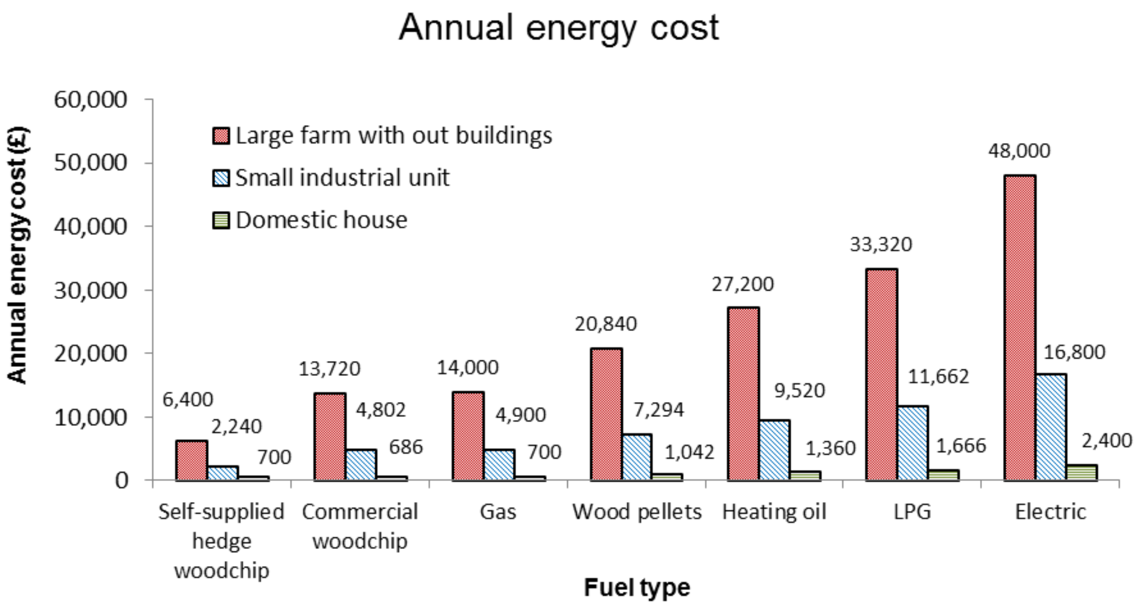

Figure 5.21. Estimated annual energy cost for three different building types using different fuels based on the unit energy cost shown in Figure 5.20. A unit energy cost for self-supplied hedgerow woodchip of 3.5 pence/kWh was used for calculating the annual energy cost for the domestic house and a unit cost of 1.6 pence/kWh for both the industrial unit and large farm with out-buildings was used

Figure 5.21 shows self-supplied hedgerow woodchip to be the cheapest fuel option when providing energy to a large enough building to warrant the use of the larger scale assisted fell and Heizohack drum chipper machinery combination (approximately 270m and above of hedge). When only providing energy to the domestic house and using the smaller scale manual fell and Timberwolf disc chipper machinery combination, self-supplied hedgerow woodchip is comparable to the cost of commercial woodchip and gas. However, if two years' supply of hedgerow woodchip for a domestic house was harvested in one year (i.e. every other year), it may then prove economical to use the larger scale machinery combination which would further decrease the annual energy cost.

5.12. Coppice regrowth

To determine the effect of different harvesting options on coppice regrowth, the regrowth on Hedge 21 at Elm Farm was measured in July 2015, seven months after being coppiced during the hedgerow harvesting trials. Fifteen metre monitoring plots were measured out in each of the five hedgerow coppicing trial sections: hydraulic tree shears (left as cut), hydraulic shears (with short chainsaw finish), hydraulic tree shears (with long chainsaw finish), assisted fell and manual fell. Both the number of shoots and the height of the five tallest stems were recorded for each stool within these 15m plots. The plots coppiced using the assisted fell and hydraulic tree shears (both long and short chainsaw finishes) had the highest average number of shoots per stool, at 89.86 and 85.91 respectively (Figure 5.22), followed by manual fell with 77.43 and then the hydraulic tree shears (left as cut) which only had 60.5 shoots per stool on average.

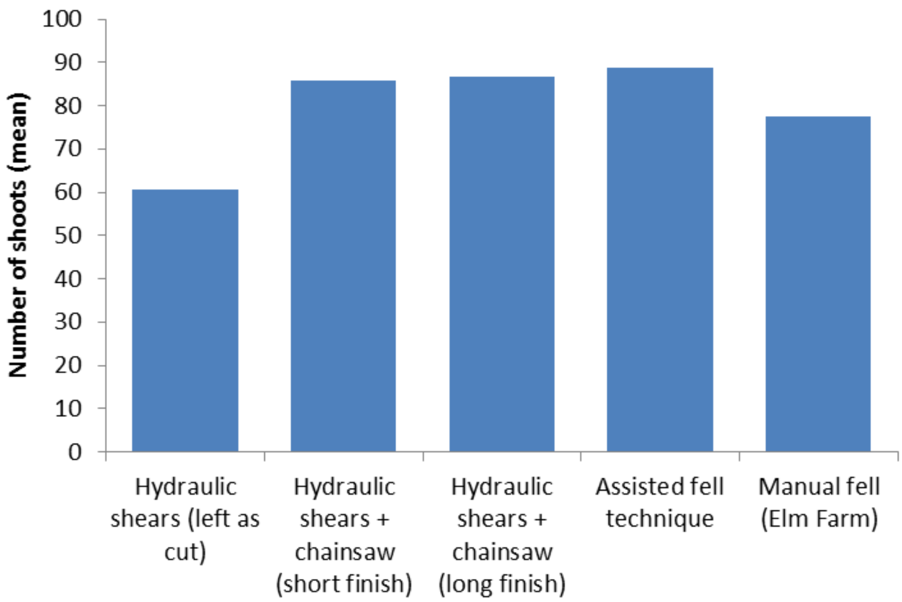

Figure 5.22. Average number of shoots per coppice stool within 15m monitoring plots recorded 7 months after coppicing and for the harvesting machinery options trialled

In terms of the average height of coppice regrowth after 7 months, the assisted fell, manual fell and hydraulic tree shears (left as cut) options had the tallest average stem heights per stool ranging from 105.38cm to 113.29cm, followed by the hydraulic tree shears (with short chainsaw finish) at 94.65cm, and then the hydraulic shears (with long chainsaw finish), which had an average stem height of 89.49cm (Figure 5.23).

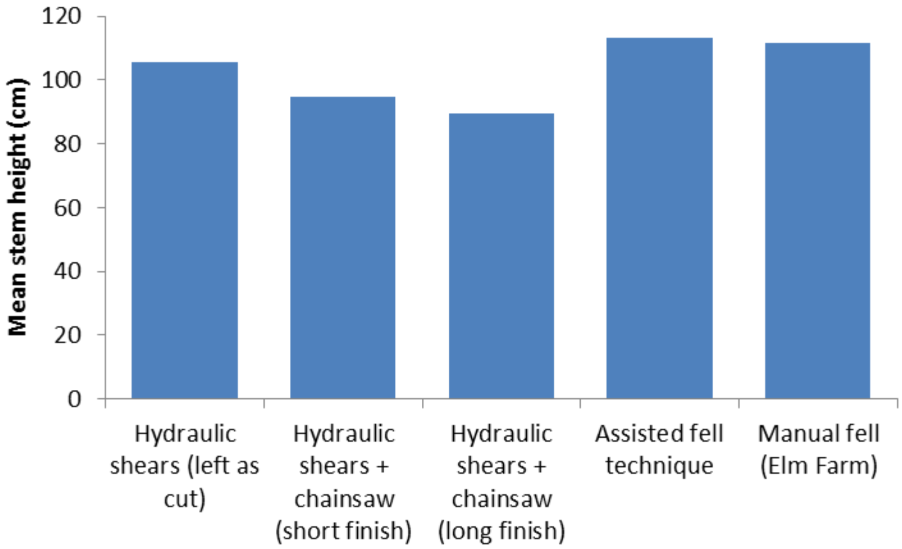

Figure 5.23. Average height of coppice regrowth stems within 15m monitoring plots recorded 7 months after coppicing and for the harvesting machinery options trialled

6. Discussion

6.1. Logistics of harvesting hedgerows for woodfuel

Machinery and contractor availability

When seeking out specific types of machinery to trial, contractors were sought and contacted. Some were keen to get involved in the machinery trials, either because they were interested in the project or saw it as an opportunity to promote their contracting business, their services or their machine being trialled, whilst others were very sceptical about the aim of the project and the usefulness of what we were trying to assess, and were not so keen to be involved.

One question mooted after the trials was whether operator experience and attitude affected results. It seemed that the machines of those contractors who were keen to be involved in the trials and understood what we were trying to achieve performed better, which may have ultimately had an influence on the quality of coppice cut and the quality of woodchip. This may however have been down to the fact that those who were positive about the trials were those who were familiar with this kind of habitat management work, and therefore had greater experience and familiarity with coppicing or chipping small diameter material, which resulted in higher quality outputs.

Hire cost

As expected, the larger scale harvesting options were found to have a substantially higher hire cost than the medium to small-scale options such as the assisted and manual fell options. For both the felling grapple and hydraulic tree shears, haulage accounted for around 50% of the day hire cost. This high haulage cost is due to use of a low-loader being required. Options such as the circular saw, assisted fell and manual fell did not require the use of a low-loader for transport and are therefore likely to be locally available in most situations. These options were therefore found to be cheaper than the larger scale options.

It is questionable whether some of the hire costs given by contractors were realistic costs. The contractor used for the felling grapple was a machinery dealer who viewed the trials as a chance to demonstrate the Gierkink felling grapple to those attending the trials. It is therefore unclear as to whether the hire cost quoted for this machine is truly representative of what a contractor would charge. Similarly, for both the circular saw and manual fell options trialled at Wakelyns Agroforestry, a local contractor who carries out the majority of agricultural operations at Wakelyns Agroforestry was used, and may have been relatively cheap compared to other contractors providing the same service. Whether or not these costs are representative, the hire cost of all options are likely to vary with the contractor used, as shown by the variation in hire cost between the two manual fell options and the two larger scale chippers.

All hire costs were based on a day rate rather than per unit of hedge coppiced (i.e. £4 per metre of hedge). Contractors were reluctant to provide a quote per unit of hedge length due to the difficulty in determining how long a job would take because of the variable nature of hedges and the extra complication of complying with the restrictions imposed by the trials. As coppicing hedges for woodfuel becomes more common it may become more common to see jobs priced on a per unit basis. One specialist hedgecutting and hedge coppicing contractor did quote on a per unit basis and quoted £3/m to coppice hedges using his tri-blade circular saw. This price is roughly comparable to the cost of coppicing Hedge 21 at Elm Farm using the assisted fell method, which worked out at £2.26/m.

Purchase cost

For harvesting options requiring the use of a tractor or excavator (i.e. all options except the manual fell), the purchase cost of a new excavator or tractor on average made up 82% of the overall purchase cost. As most farmers are likely to have access to a tractor and/or excavator, it is better to compare the purchase cost of harvesting options without this additional cost. When the cost of a tractor or excavator is excluded, the assisted fell is considerably cheaper at £2,400 than the other medium and large scale options which vary from £9,900 to £15,000. Manual fell had the lowest purchase cost at £900, as this method only involves the purchase of a chainsaw and personal protective equipment (not included in this purchase cost).

The Heizohack drum chipper had the highest purchase cost at £120,000, followed by the Jenz drum chipper at £105,000. The Heizohack was a larger capacity machine able to chip larger diameter timber and therefore with a potentially higher output of woodchip per hour. This higher purchase cost may explain why the Heizohack had a higher hire cost. Both the larger scale chippers had a significantly higher purchase cost than the Timberwolf disc chipper at £14,500.

All the figures quoted here are net of VAT, but all new and most secondhand machinery will incur VAT and so needs to be taken into consideration when budgeting.

Ease and safety of machinery operation

The rate of hedgerow coppicing for all methods appeared to be dependent on the mean diameter and volume of the hedgerow material, the proportion of large diameter trees, and the quantity of work to be done, but this was most noticeable with the manual felling method.

For the tree shears and felling grapple, the ease of using these machines to coppice hedges may well depend on operator experience, and particularly experience of felling and handling small diameter and multi-stemmed material. The circular saw and manual fell methods worked best on small diameter coppice material less than 5m tall, and both struggled where the hedge was taller and there were larger single-stemmed trees. The circular saw method needed the larger trees to be felled manually, and the manual fell method struggled to handle larger diameter cordwood and extract tall brushwood without the assistance of a machine. The assisted fell method worked well whatever the diameter of timber and coppiced the hedge with ease, although it did require an intimate working methodology, with some health and safety concerns.

The tree shears did not perform optimally on the multi-stemmed coppice material it was trialled on at Elm Farm; however they were not tested on a hedgerow (or woodland setting) comprising predominantly single-stemmed trees. The limitations of the tree shears were exposed, perhaps unfairly, given that they are designed to cut and fell single-stemmed material. Tree shears in general are by their nature more robust against stones and metal which may be encountered when coppicing hedges such as old fencing wire, than saw blades which can be thrown when they catch a stone or even when cutting wood on occasion, and are prone to damage by metal objects with potentially very expensive consequences.

There are some health and safety concerns with both the circular saw and assisted fell methods of coppicing which should be highlighted. Comments from spectators were made that circular saws are just too dangerous to use and shouldn't be considered as a machinery option when considering hedgerow coppicing. The concerns are the dangerous nature of an exposed high speed saw blade and the lack of directional control of falling material, with concerns about material falling onto the tractor cab. However a single blade circular saw is used annually for cutting small diameter SRC (short rotation coppice) willow and hazel at Wakelyns Agroforestry, and Andrew Hawes & family, specialist hedgecutting contractors based near Henley-on-Thames in Oxfordshire routinely use multi-blade circular saws for coppicing hedgerows.

The assisted fell method of hedgerow coppicing demands a very experienced team who are used to working together, due to the intimate nature of the working methodology. There are health and safety concerns with regards to the manual feller working near or under the excavator arm when the machine is running. Englefield Estate commonly use this felling method and have completed a risk assessment of it which they consider satisfactory.

There are also health and safety issues with regards to the manual fell method of hedgerow coppicing, but as with all manual work these are related to manual handling and safe personal lifting limits. The physical strength limitation and personal safe lifting limit means the manual felling method is not suitable where there are large single-stemmed trees, or where the hedge is more than approximately 5m tall, and in this situation a tractor or excavator should be used to assist the manual feller and to take the brunt of the physical work involved in controlling the direction of tree felling and in extracting and moving the timber. Tall trees and particularly those leaning the wrong way should be roped and tied to a large vehicle when using the manual felling method to guide the direction of fall and ensure the felling is safe.

The use of a purely manual fell approach on Hedge 1 at Wakelyns Agroforestry (a hedge with several tall trees) without the assistance of a tractor to aid felling and moving coppice material did not work well. This resulted in health and safety concerns and the use of a tractor would have likely made the manual fell safer and much faster.

The main difference between the three chippers trialled, with regards to their operation was the method of feeding the hedgerow material into the chipper. The small scale Timberwolf disc chipper was manually fed, whereas both of the large scale drum chippers were crane fed. This single difference was what had the greatest impact on the processing of hedgerow material, impacting on the manpower required, the ease of extraction of stacked hedgerow material, ease of feeding the chipper and overall ease of operation, as well as the throughput of timber and the rate of woodchip production.

Fuel use

As fuel costs are included in the hire cost of harvesting and chipping machines, fuel consumption does not affect hire cost. However if purchasing machinery, fuel consumption per metre of hedge may be of interest. The two harvesting options with the highest fuel use per metre were the felling grapple (0.5 litres/m) followed by the circular saw (0.43 litres/m). Both these options were trialled on Hedge 1 at Wakelyns Agroforestry where there was larger-stemmed material which may explain their higher fuel consumption. Both the hydraulic tree shears and assisted fell options had a similar fuel use per metre (0.32-0.33 litres/m) and were trialled on Hedge 21 at Elm Farm. The two manual fell options had the lowest fuel consumption as they do not require the use of a tractor or excavator; however the manual fell option trialled at Elm Farm had a higher fuel use than manual fell at Wakelyns Agroforestry. This may be explained by Hedge 21 at Elm Farm having a large amount of blackthorn outgrowth and multi-stemmed hazel stools requiring more chainsaw work than the single stemmed trees of Hedge 1 at Wakelyns Agroforestry. It is also important to remember that the fuel consumption of these options was only estimated by the contractors, and that the different size chainsaws used by the contractors may have had differing fuel consumption rates, though this is likely to be minimal. Fuel consumption is more likely to be dependent on the time taken to coppice a section or the revs the machine operated at for the majority of the time.

Fuel use was less variable between the chippers with the Heizohack drum chipper using the most fuel per metre (0.63 litres/m) followed by the Jenz drum chipper (0.50 litre/m) and the Timberwolf disc chipper (0.45 litre/m). Once again it is difficult to ascertain whether these differences are due to the nature of the material being chipped or the machines themselves. Engine size and the length of time chipping will affect fuel consumption; both the larger drum chippers were driven by the tractor which was over 100hp, whereas the small Timberwolf chipper was self-driven by a 35hp engine.

Maximum efficiencies

Maximum efficiency refers to the maximum length of hedge each machine can harvest or process in an eight hour working day (one hour for lunch/breaks, seven hours of cutting/chipping time). This was calculated from the average time taken for each machine to cut or chip a set length of hedge or hedge material.

Due to the harvesting and chipping options being used on different hedge types it is difficult to make direct comparisons between the machines. For example, both the hydraulic tree shears and felling grapple options are likely to be better suited to large diameter single-stemmed material. However, the hydraulic tree shears were only trialled on Hedge 21 at Elm Farm, a hazel coppice hedge with small diameter material, and the felling grapple was only trialled on Hedge 1 at Wakelyns Agroforestry, a hedge with lots of single-stemmed field maple trees, so material it was well suited to.

It would therefore be unfair to compare the maximum efficiency of the hydraulic tree shears to that of the felling grapple when the tree shears were trialled on sub-optimal material. As shown by the variation in maximum efficiency of the circular saw and manual fell options when used on different hedge types, the nature of the hedge material being coppiced can have a significant effect on the performance of harvesting options. On average using a chainsaw to tidy up the cut of the hydraulic tree shears added 0.52 minutes of cutting time per metre. This additional time and labour results in a lower maximum efficiency and higher cost per metre than using the tree shears on their own. Whether this increase in cost is compensated for by better coppice regrowth is questionable, with no obvious differences in regrowth between plots coppiced using different options being found 7 months after coppicing.

Manual fell (when unassisted by a tractor) and the circular saw were well suited to smaller diameter hedge material such as hazel coppice and had high maximum efficiencies when used on such material.

Both of the larger drum chippers had higher maximum efficiencies than the Timberwolf disc chipper (84m/day). Despite being of a similar specification, the Heizohack chipper had a higher efficiency (284m/day) than the Jenz chipper (258m/day). The Heizohack was a larger capacity machine able to chip larger diameter timber and with a potentially higher output of woodchip per hour. To what extent the difference in maximum efficiencies is down to the higher capacity or to other factors such as the way the chippers were set up, the different operators or the type of material being chipped is unknown.

The maximum efficiency of a harvesting or chipping option may vary with the contractor used, their familiarity with the machine or technique, and experience of dealing with hedge material. For example the assisted fell team were a father and son partnership who had worked together for 30 years. This raises the question as to whether a less experienced team would be able to coppice at a similar rate (266m/day).

One issue with testing the options under a trial setting is that harvesting contractors were asked to cut short lengths of hedge each (20 to 50m). For many of the options these lengths were well below their maximum efficiencies. In observations of the manual fell option trialled at Elm Farm, it is questionable whether the two person team would work at the same rate if they were faced with 100m of hedge to coppice, i.e. they may well have coppiced more quickly with a larger task ahead of them.

The fact that the contractors were timed and under observation by researchers may have also influenced work rates. In order to record many of the parameters, such as woodchip weight and volume, work was interrupted so that these measurements could be taken or discussions had about the work being undertaken. Although time taken to collect this data was not included within cutting and chipping times, these interruptions may have negatively impacted the maximum efficiencies of some options.

6.2. Quality of coppice cut

Coppicing carried out with a chainsaw (manual fell, assisted fell and felling grapple) resulted in good clean cuts which would be expected to minimise disease ingress and optimise coppice regrowth. The felling grapple with integral chainsaw and the circular saw could cut stems cleanly, but the finish was variable because the angle of cut was limited. Other cutting mechanisms using a saw, such as the circular saw could cut stems well but not as cleanly as a chainsaw blade, resulting in a lot of splinters around the edges of stems. Neither the felling grapple nor the circular saw cut very small diameter material so well.

The hydraulic tree shears were clearly designed to cut or harvest single-stemmed trees and not small diameter shrub and coppice material, with some stems left with untidy rough cuts with splinters, deep splits down stems into the stool or cut very high because of limited manoeuvrability. Seemingly because of poor visibility of the cutting bar or shears, the tree shear head was generally tilted below horizontal, resulting in pressure being applied to the coppice stool by the tree shears which caused some visible movement of the stool, root rock or root disturbance which gave concern about disease ingress and regrowth. It was also not clear how much of the quality of coppice cut was due to the machine design or the operator experience at harvesting small diameter material.

Coppice regrowth

To determine the effect of different harvesting options on coppice regrowth, the regrowth of Hedge 21 at Elm Farm was measured in July 2015, seven months after being coppiced. The plots coppiced using the assisted fell and hydraulic tree shears (both long and short finishes) had the highest average number of shoots per stool, at 89.86 and 85.91 respectively, followed by manual fell with 77.43 and hydraulic tree shears (left as cut) with 60.5. Plots cut using the assisted fell, manual fell and hydraulic tree shears (left as cut) had the tallest average stem heights per stool ranging from 105.38cm to 113.29cm, followed by the hydraulic tree shears (with short chainsaw finish) at 94.65cm, and the hydraulic tree shears (with long chainsaw finish) at 89.49cm. Overlapping standard deviations suggest that there are no obvious differences in coppice regrowth among plots cut using different methods. The small variation between plots is therefore likely to be due to variation in growing conditions along the hedge or the health of the stools before coppicing. A smaller number of stems re-growing from each stool may well result in a greater rate of regrowth, i.e. taller regrowth.

6.3. Woodchip quality

It was expected that the greatest difference in woodchip quality would be whether the hedgerow material was chipped with a disc chipper (with no screens) or a drum chipper with integral screens designed to produce biomass i.e. woodchip for fuel, with the expectation that the biomass drum chippers would produce higher quality woodchip than the disc chipper.

The small Timberwolf disc chipper produced clean but small woodchip, with quite a lot of it being only 10-15mm diameter, and as expected there were quite a few long thin little sticks because there was no screen. The Jenz drum chipper produced good quality woodchip on visual inspection, with relatively few shards or long bits of stick. The Heizohack drum chipper produced similar woodchip, but with some large oversize woodchips and a larger quantity of long shards and slithers. This suggests that the screen in the Jenz chipper was more effective or a more appropriate diameter than the screen in the Heizohack chipper, if indeed the screen was in place.

On the basis of a visual assessment the woodchip quality appeared to be better, from both the Timberwolf and the Jenz chippers than that produced by the Heizohack chipper, but this may in part have been down to the fact that the woodchip produced by the Heizohack chipper was the only material to have been chipped fresh and green. After three months of this woodchip self-drying in a covered but open-ended barn some mould had formed and where the moisture had vented out from the pile of woodchip there was some dark discolouration of the woodchip. This self-drying process therefore resulted in a less appealing looking ‘dirty’ chip.

Commercial woodfuel suppliers usually sell woodchip classed as G30 and G50 under the ÖNORM standards. Despite the perceived differences observed visually, the woodchip produced from whole-tree hedgerow material by all three chippers during these trials was classed as G30 under the ÖNORM standards and P16B under the BS EN standard. This indicates that woodchip produced from hedge material can have a similar particle size distribution to commercially available woodchip produced from virgin roundwood.

Little variation in calorific content was found between the whole tree woodchip produced from the three different hedges whether chipped dry or green. Woodchip produced from Hedge 1 at Wakelyns Agroforestry had the highest calorific content at 19.41 MJ/kg and woodchip from Hedge 2 at Wakelyns Agroforestry had the lowest at 19.06 MJ/kg.

The ash content of woodchip produced from hedge material that had been left to dry *in situ*, which was chipped by the Timberwolf disc chipper (Hedge 21 at Elm Farm) and Jenz drum chippers (Hedges 1 & 2 at Wakelyns Agroforestry), ranged from 2.06% to 2.93%, whilst the woodchip produced from Hedge 21, where the material was chipped green by the Heizohack drum chipper, had the highest ash content at 3.58%. It is not clear why this is the case, although during the four months the hedgerow material was left out in the field to air-dry, any remaining leaves, some bramble material and bark are likely to have dropped off, which may have resulted in a ‘cleaner’ woodchip with lower ash content.

Woodchip produced from material left to dry for nearly four months *in situ* before chipping was found to have an average moisture content of 24%, while the self-dried woodchip produced from green material had a moisture content of 30.58% after the same period. A lower moisture content can therefore expected from woodchip produced from air-dried or seasoned material.

Woodchip quality after cordwood extraction

Although logs are often used as a fuel source in open fires, wood stoves and boilers they require considerably more time and labour to produce them compared to woodchip due to splitting, seasoning and transport. Following the extraction of logs from hedgerow coppice material a large amount of brash (small branches and twiggy material) is also left and usually burnt in a bonfire *in situ*. Woodchip produced from whole trees however makes use of 100% of the biomass extracted.

To explore the productivity of firewood logs from hedges and whether the resulting brash following their extraction could be chipped and used as woodfuel, cordwood was extracted from two sections of whole-tree hedgerow coppice material from Hedge 1 at Wakelyns Agroforestry. The remaining brash was chipped and sent for woodchip quality analysis. For one of the two sections of hedge material, contractors were asked to extract all the cordwood over 10cm in diameter, and for the other section the contractors were asked to extract the easily accessible cordwood over 10cm in diameter, which they thought economical in terms of firewood value versus labour cost. For both sections cordwood made up around 60% of the biomass extracted and the brash 40%.

The woodchip quality results indicate that the more cordwood that is extracted the lower the calorific content of the woodchip produced. Whole-tree woodchip from Hedge 1 had a calorific content of 19.41 MJ/kg, while woodchip produced from the brash after cordwood extraction had a calorific content of 18.99 MJ/kg when extracted down to an economic diameter and 18.86 MJ/kg when extracted down to 10cm diameter.

As would be expected the woodchip produced from brash when the cordwood had been extracted down to 10cm also had a higher ash content (3.83%) than the whole-tree woodchip from Hedge 1 (2.93%). However, the woodchip from the brash where cordwood was extracted to an economical diameter had a lower ash content (2.42%) than the whole-tree woodchip. This result is unexpected, and perhaps anomalous, as it is assumed that a higher percentage of twiggy material would increase the ash content as was seen with the brash-based woodchip sample.

Both of the brash-based woodchip samples failed BS EN and ÖNORM (G50) standards for particle distribution, indicating a large percentage of finer material (<5.6mm) within the woodchip. However the woodchip produced from the brash where logs were extracted down to 10cm was classed as G30 under the ÖNORM standards as it contained fewer woodchips over 16mm than the other brash- based woodchip sample.

With only one sample of each category of brash-based woodchip having been tested and given the inherently variable nature of woodchip, it is very difficult to draw sound conclusions from these results. To make any meaningful conclusions on hedgerow woodchip quality further data is needed. It would however seem that if logs are extracted, the resulting woodchip produced from the remaining brash will be of lower quality. This low quality chip could however have other uses such as mulch, path surfacing, animal bedding or when composted could be used as a soil conditioner.

6.4. Economics

Production costs of hedgerow woodchip

Both harvesting and chipping costs per metre were calculated by dividing the day hire cost including haulage by the number of metres of hedge each machine can harvest or chip in one day, i.e. the maximum efficiency of each option. Of the harvesting options trialled on Hedge 21 at Elm Farm, the assisted fell technique was found to have the lowest harvest cost per metre (£2.26) followed by the hydraulic tree shears left as cut (£6.78), manual fell (£6.85) and hydraulic tree shears with chainsaw finish (£8.06). On Hedge 1 at Wakelyns Aroforestry the felling grapple had the lowest cost per metre (£6.28) followed by the circular saw (£7.46) and manual fell (£8.24). On Hedge 2 at Wakelyns Agroforestry, the thin hazel coppice, the circular saw had a harvest cost of £4.00 per metre indicating that the circular saw is better suited to small diameter material. Of the chipping options trialled the Jenz drum chipper had the lowest processing cost per metre (£2.44), followed by the Heizohack drum chipper (£3.21) and the Timberwolf disc chipper had the highest processing cost (£5.01).

As the hedgerow woodchip production cost is the cost per metre of harvesting and chipping combined, the production cost per metre varies with the combination of harvesting and chipping machinery used. Production cost will also vary with hedge length. If an expensive machine capable of chipping 250m of hedge material in a day is hired to chip only 50m of hedge material, the cost per metre will be higher than if you had enough hedge material to keep the machine working for a full day. For both harvesting and chipping options the lowest cost per metre is reached when the hedge length reaches a multiple of the machines' maximum efficiency in a day.

It is therefore advisable to match harvesting and chipping options to the length of hedge to be coppiced. If only a short section of hedge is to be harvested (less than 150m) it will be more economical to use small scale machinery options such as manual fell with chainsaw and a manually-fed disc chipper than the larger scale options. If using larger scale machinery options such as the assisted fell technique and a crane-fed drum chipper, it is important to have enough hedge length and material to keep the machines busy for a full day. This could be achieved by storing or leaving harvested material *in situ* until enough biomass has accumulated to warrant the use of a large scale chipper. Alternatively, neighbouring farms could collaborate and share the cost.

Potential savings from reduced hedgerow flailing

Most hedges in the UK are managed by flailing with a tractor-mounted hedge cutter. This is often carried out annually, particularly on arable farms and roadside hedges. Managing hedges by flailing takes time and costs money every year, but earns nothing in return. It is estimated to cost 88p per metre (in diesel, machinery costs including wear and tear, depreciation, and labour) to flail the top and sides of a 2m hedge each year (SPON's External Works and Landscape Price Book, 2014). Over 15 years this amounts to a cost of £13.20 per metre. By coppicing a hedge the need for regular hedge flailing is reduced to just side trimming every three years to control outgrowth if necessary.

The maximum potential savings from reduced hedgerow flailing were calculated for different machinery combinations on the basis that all machines were used at their maximum efficiency and that hedges were coppiced on a 15 year rotation and side flailed four times over this period. For Hedge 21 at Elm Farm a saving was only made when the assisted fell option was used with either the Heizohack (£4.22/m) or Timberwolf chipper (£2.41/m). All other machinery combinations trialled at Elm Farm do not incur a saving and cost £0.31 to £3.39 more per metre than flailing annually. For Hedge 1 at Wakelyns Agroforestry only the felling grapple used with the Jenz chipper made a saving (£0.95/m). The circular saw and manual fell cost £0.22 and £1.00 per metre more than annual flailing respectively. When used on Hedge 2 at Wakelyns Agroforestry however the circular saw made a saving of £3.23 per metre. Although the potential savings from reduced flailing would seem limited, it is important to remember that these savings and costs do not take into account the market value of the product produced i.e. the hedgerow woodchip, which can either be used on farm or sold locally.

Based on the above costs, for a farm with 10 miles/16.1km of hedges, of which half are managed by coppicing for woodfuel, and therefore approximately 400m of hedge are coppiced every year (using the assisted fell technique, side trimming every three years and chipping using a large crane-fed drum chipper such as the Heizohack), savings of £29,880 over a period of 15 years could be made. These potential savings from coppicing will however vary with hedge type and coppicing and chipping methods used. All costs include haulage of machinery to site, but do not include the potential cost savings from using the woodchip as fuel, or the income generated from the sale of the woodchip.

Potential profits from sale of hedgerow woodchip

Having taken into account the harvesting (coppicing) and chipping costs of producing hedgerow woodchip, the potential profits from selling hedgerow woodchip locally were explored using a ‘best case scenario’ approach, where the highest offer of £75 per tonne (or £18.75/m³ at 30% MC) was used in the analysis. The cost of transporting the woodchip to the buyer was not included in the analysis as this cost will vary with the volume of woodchip and the delivery distance.

Despite the highest price per tonne being applied, the only machinery combination where a profit was made (£1.34/tonne) was the felling grapple and Jenz chipper used on Hedge 1 at Wakelyns Agroforestry. All the other machinery combinations made a loss per tonne. These losses ranged from £10.77 per tonne when using the assisted fell technique and Heizohack chipper to £130.28 per tonne when using the hydraulic tree shears with chainsaw finish and Timberwolf chipper.

However, when both the income generated from selling the hedgerow woodchip and the savings from reduced hedgerow flailing were combined a more positive outcome was presented. This scenario was named ‘profit from sale of hedgerow woodchip with flailing savings’ as shown in Table 5.4. Under this scenario, a net profit was achieved for two of the machinery combinations. The felling grapple and Jenz chipper machinery combination (on Hedge 1 at Wakelyns Agroforestry) achieved a net profit of £9.35/tonne, and the assisted fell and Heizohack chipper combination (on Hedge 21 at Elm Farm) made a net profit of £55.49/tonne. A net loss was made for all of the other machinery combinations trialled, but three machinery combinations were also close to break even.

Looking at the machinery combinations and the hedge types which proved to be the most profitable, it can be seen that it was where the harvesting method best matched the size and volume of hedge material to be coppiced that hedgerow coppicing proved to be most profitable. It is also true that the harvesting cost was lowest where the diameter and volume of hedge material was lowest, but in terms of net profit this would be offset by a lower income received from a smaller volume of woodchip.

It should be noted however that the figures presented in Table 5.4 are based on using each machine at its’ maximum efficiency, and on a generous market value of £75/tonne or £18.75/m³, where the second highest offer was £52.80/tonne or £13.20/m³. These figures therefore present the most favourable and profitable scenario. To achieve these savings in practice, each option would need to be used at its maximum efficiency which may require hedge material being stored until enough material has been accumulated to keep the larger chippers working hard for a full day. The net profit could be further improved if a coppiced hedge was side flailed less frequently than every three years, where it is not necessary to control outgrowth so much, increasing the flailing savings.

From the data gathered from these two hedgerow harvesting machinery trials, it would seem that selling hedgerow woodchip may only just break even or make a small profit even when the highest offer per tonne was used. It is very encouraging though that when the full production costs are taken into account a break even or small profit is achievable, and if the energetic value of the woodchip is offset against the cost of other fuels, the cost savings are even greater. Using hedgerow woodchip on-farm as a source of self-supplied woodfuel and a substitute for bought in fossil fuel-derived energy is therefore likely to prove to be most economical scenario.

Unit energy cost of hedgerow woodchip

The unit energy cost refers to the production cost of a unit of energy (one kilowatt-hour) for hedgerow woodchip when produced using different machinery combinations. This is calculated by dividing the cost of producing one tonne of woodchip (including harvesting and processing costs, but not including storage costs) by how many potential kilowatt-hours (kWh) that tonne can produce. The number of kWh contained within a tonne of woodchip was determined by converting the calorific content (MJ/kg) of the woodchip produced by each of the three hedges into kWh. Again the costs per unit of energy have been calculated on the basis that all machines were used at their maximum efficiencies and therefore the lowest production cost per unit of energy (kWh) possible for these machinery combinations based on our data.

For Hedge 21 at Elm Farm, the assisted fell and Heizohack drum chipper combination realised the lowest cost per unit of energy at 1.6 pence/kWh, followed by the assisted fell and Timberwolf disc chipper (2.1 pence/kWh). The hydraulic tree shears with chainsaw finish and Timberwolf chipper had the highest cost per kilowatt-hour at 3.9 pence/kWh, followed by the hydraulic tree shears with chainsaw finish and Heizohack chipper (3.3 pence/kWh). Both manual fell and the hydraulic tree shears had a similar cost per kilowatt-hour regardless of which chipper was used (between 2.9 and 3.5 pence/kWh). At Wakelyns Agroforestry the lowest cost per kilowatt-hour was realised using the felling grapple and Jenz drum chipper (1.4 pence/kWh), followed closely by the circular saw and Jenz chipper on Hedge 1 (1.5 pence/kWh) and manual fell and Jenz chipper (1.7 pence/kWh).

The reason the unit energy costs (p/kWh) are lower for those machines trialled at Wakelyns Agroforestry compared to those trialled at Elm Farm, is that despite having higher production costs, Hedge 1 at Wakelyns Agroforestry (118.5 kg/m) had a biomass productivity almost double that of Hedge 21 at Elm Farm (63.69 kg/m). Hedge 1 therefore produced almost twice as much fuel and energy per metre compared to Hedge 21. This is also illustrated by the use of the circular saw on Hedges 1 and 2 at Wakelyns Agroforestry. Hedge 1, had a biomass productivity of 63.69kg/m and resulted in an energy cost of 1.5p/kWh, whereas Hedge 2 with a productivity of 41.34kg/m resulted in an energy cost of 2.9p/kWh, despite the same machine being used.

The energy cost of hedgerow woodchip, which ranged from 1.6 to 3.5 pence per kWh depending on machinery options and hedge type, would seem relatively favourable when compared to the cost of commercially produced woodchip from forestry roundwood (3.43p/kWh), natural gas (3.5p/kWh), wood pellets (5.21p/kWh), heating oil (6.8p/kWh), LPG (8.33p/kWh), and electricity (12p/kWh) (Forest Fuels, 2015).

To bring these energy unit costs into context, the annual energy cost for three types of building were calculated based on the energy unit cost (pence/kWh) of other fuel types and woodchip produced from Hedge 21 at Elm Farm. As substantially less hedge material is needed to produce enough woodchip to meet the annual energy demands of a domestic house (59m of hedge) compared to a small industrial unit (412m) and large farm with outbuildings (1178m), the annual energy cost of a domestic house was calculated assuming small scale machinery options (manual fell and Timberwolf disc chipper) were used. For both the small industrial unit and large farm with outbuildings the annual energy cost was calculated assuming a large scale machinery combination (assisted fell technique and Heizohack drum chipper) were used.

The results indicate that self-supplied hedgerow woodchip is the cheapest fuel option when providing energy to a small industrial unit and large farm with outbuildings. When only providing energy to a domestic house self-supplied hedgerow woodchip is comparable to the cost of commercial woodchip and gas. If however two years' supply of hedgerow woodchip for a domestic house was harvested in one year (i.e. every other year), it may then prove economical to use the larger scale machinery combination which would further decrease the annual energy cost.

Using hedgerow woodchip on-farm could therefore not only incur savings from reduced hedgerow flailing, but also provides a source of local, renewable and sustainable, and carbon-neutral low cost energy.

Market value of hedgerow woodchip

The market for woodchip from hedges is still developing and there is currently limited information on sale prices. Opportunities for selling hedgerow woodchip include community woodfuel co-operatives, woodfuel hubs, selling directly to neighbours with woodfuel boilers, and to self-suppliers. To explore the market for woodchip from hedges, potential buyers for the woodchip produced by the Elm Farm trial were found and asked to value the woodchip and provide quotes.

Samples of the woodchip from Hedge 21 at Elm Farm, both of that chipped green and that chipped dry were given to a potential buyer to trial. This potential customer was a local farmer and woodfuel self-supplier from Baydon Hole Farm with a HDG 100kW Compact woodchip boiler, where the woodchip is fed from a 10m³ bunker via a 6"/15cm auger and star wheel doser onto the burning grate. He ran each sackful through his system, and found that the woodchip didn't block his automatic auger feed system, and fed through to the boiler despite the presence of some shards and slithers. He did however suspect that the woodchip would have a higher ash content than the predominantly cordwood derived woodchip which he normally produces and uses, which would mean that the ash tray would need emptying more often, and therefore that the ash extraction setting would need adjusting. He did make an offer of £75/tonne or £18.75/m^3 (at 30% MC and not including transport to buyer) for the Elm Farm hedgerow woodchip, but after his trial with it and further consideration he decided not to purchase it, although this decision is likely to have been influenced by him currently having sufficient timber material to keep his woodchip boiler going for the time being.

The hedgerow woodchip harvested at Wakelyns Agroforestry will be used in the on-farm woodfuel boiler, a Gilles HPK-RA20 20kW woodchip boiler which heats the farm house. It is usually fuelled by the hazel and willow short rotation coppice woodchip grown on the farm as part of the agroforestry trials which take place there. The woodchip boiler was installed in 2007, and the owner is very happy using coppice woodchip, finds it perfectly satisfactory and only occasionally has blockages. The boiler is checked regularly, but he is always surprised by how little ash is produced, only having to empty the ash pan every two weeks in winter.

A local forestry consultant and Director of the Hampshire Woodfuel Co-operative (HWFC) originally offered £10.20/m^3 for the Elm Farm hedgerow woodchip (not including transport to buyer), if the Organic Research Centre became a member of HWFC, but once the woodchip had all passed the G30 ÖNORM standard he offered £13.20/m^3. This difference in price was at least in part because prior to the G30 pass it was assumed that the Elm Farm hedgerow woodchip would have to go through the HWFC drying and screening process. Subsequently another quote of £18-20/m³ (including transport to buyer) was given for the Elm Farm G30 hedgerow woodchip in September 2015 by South East Woodfuels, proving that there is a market for it and at a reasonable rate.

Due to the limited number of quotes received for the hedgerow woodchip, it is hard to know what the real market value for it is, though it appears to be dependent on how happy the buyer is to use it and whether it meets their and their boilers' needs. The highest price offered (£75/tonne or £18.75/m^3) was from a local self-supplier who managed on-farm wood resources as fuel for the woodchip boiler on site. It seemed therefore that the buyer was familiar with using woodchip of a lower quality, understood that it was still a viable, calorie-rich and sustainable fuel, and did not mind that the hedgerow woodchip would be lower in quality to that of commercially available woodchip produced from virgin roundwood.

The lower quotes were from a local woodfuel co-operative (HWFC), where the woodchip would be sold on to its customers. Although the woodchip produced from Hedge 21 was classified as G30 chip under the ÖNORM particle distribution standards, woodchip quality, especially that of the high ash content (2-4%), was of concern to the co-operative. Commercial woodchip is expected to have an ash content under 1%, so those using the hedgerow woodchip would have to adjust their boiler and de-ashing system to cope with the higher ash content.

When contacted, some woodchip merchants or woodfuel hubs (William Hamer and HWFC) said that if they buy in lower-grade woodchip, such as hedgerow woodchip or woodchip produced from arboricultural arisings, it is likely to be screened to remove both fines and shards (undersize and oversize particles) and blended with other higher quality woodchip produced from roundwood, in order to reduce the high ash content. The cost of this processing was quoted at £4.00 per cubic metre.

In the course of this work, exploring the potential and feasibility of hedgerow woodfuel, there seems to be some prejudice against woodchip from hedgerows, and an automatic assumption that hedgerow woodchip is second-rate low-grade woodchip. A local forestry consultant and Director of the Hampshire Woodfuel Co-operative (HWFC) made the point that the UK woodfuel market is a young market that has worked hard to establish its credibility and the quality of the woodchip fuel it is providing. The market has been built on the processing of forestry material i.e. virgin roundwood, although the woodchip market was originally conceived and developed as a market for low grade timber, such as lop and top, prunings, small branches and brash, which was often previously wasted and left in woodlands to rot, unless there was a local combined heat and power plant within an economical haulage distance (within 40 miles).

Despite woodfuel standards being developed and adopted in the UK, such as the ÖNORM and BS EN standards, to ensure a consistency and minimum quality for woodchip, judgements on the quality of timber feedstock material and woodchip are made at least to some extent on the basis of visual appearance, rather than purely on physical characteristics confirmed by woodchip quality analysis results according to at least one woodchip merchant. It is true that visual properties do relate to the quality of the fuel, in terms of it moving and flowing more easily, not blocking up, burning cleanly, ash quality and ash build up, but it is interesting that in an industry with set physical standards, visual appearance still appears to have an important role to play.

Markets for hedgerow woodchip

Using hedgerow woodchip in an on-farm woodfuel boiler is likely to prove to be the most economically viable option. However, if the woodchip cannot be used on-farm or on the holding, and if hedgerow woodchip is regarded as a second-rate, low-grade woodchip equivalent to that produced from arboricultural or tree surgeons' arisings, which are seen as a waste product, then what markets are available to the producers of hedgerow woodchip?

Through the sale of woodchip from Elm Farm, it has been shown that it can be sold and indeed quotes were received from two woodfuel merchants/suppliers and a farmer self-supplier. These quotes took into account the higher ash content, but with the backup of the woodchip quality analysis results, acknowledged that it met the industry ÖNORM standard for G30 grade woodchip. The quotes were therefore less than for grade 1 woodchip produced from virgin roundwood, as expected, but those woodchip suppliers with a pragmatic view made it clear that a lower grade woodchip could either be sold to customers with larger commercial or industrial size woodfuel boilers, such as commercial glasshouse growers, or used by themselves in their own on-site woodchip-drying plant fuelled by a large industrial woodchip boiler. Alternatively the woodchip could be screened to remove both fines and shards and/or blended with other higher quality roundwood woodchip with a lower ash content in order to reduce the overall ash content. As with the contractors involved in the machinery trials, those woodfuel suppliers who engaged with and were interested in the concept behind the use of hedgerow woodfuel were more positive about its use and a market for it.

Unlike forestry roundwood, which can be transported to a woodfuel hub unprocessed as cordwood, hedgerow material needs to be processed on-site because it is too bulky and difficult to handle and transport easily. Although hedgerow woodchip is less bulky than unprocessed hedgerow material, it is still less dense and more bulky than transporting roundwood to be processed into woodchip. As the transport costs of woodchip are higher than for cordwood per cubic metre, the embedded transport costs for roundwood or forestry woodchip per cubic metre are considerably less than for hedgerow woodchip.

Hedgerow material not only requires an additional level of processing before it can be sold, which needs to be organised logistically and budgeted for financially, but it is also more expensive to transport, further adding to the argument that it is best used on-site, on-farm or as locally as possible. These are both extra costs which have to be outlaid before income from the sale of woodchip can be received, yet another factor contributing to the economic viability of harvesting hedgerow woodfuel being marginal.

A farmer and estate management contractor from Broadmead Estate Services who visited the Elm Farm trials suggested that the unprocessed hedgerow material could be baled up with metal strapping, using a machine similar to that which wraps cling film round pallets of bricks or large hay bales to make silage. A Belgian colleague from Agrobeheercentrum Eco² has come across a machine called a press-collector which has been designed to solve this problem. It has a lorry base with folding sides which compress the bulky hedgerow material down after it has been stacked on. The press-collectors which are currently available have been developed for forestry and are unfortunately too wide to operate on public roads, however new bespoke-built machines could be adapted. This compaction process would significantly reduce the volume of the material and make it easier to handle, move and transport. It could then be removed from the field so as not to impact on agricultural operations, and stored in a yard for several months to air-dry, before it was chipped. In this compacted form, perhaps it would be economical to transport it to a large woodchip supplier or woodfuel hub who could process it into woodchip more economically with a large chipper, and where it could then be screened and/or blended as required.

6.5. Collaborative working to make hedgerow woodfuel work

Some of the higher costs involved in using and processing hedgerow woodfuel could be reduced by working in the most cost-effective way. As the harvesting of hedgerow woodfuel is likely to be relatively small scale and localised, compared with large scale forestry operations, the opportunities to reduce costs at every stage of the process by pooling resources and working collaboratively with neighbours, local farmers and woodchip users should not be dismissed.

Where a farmer carrying out a small amount of hedgerow coppicing every year for on-farm needs may be restricted to using a smaller chipper because of the more affordable hire cost, collaboration with neighbouring farmers and landowners may well make it viable to hire in a large crane-fed chipper instead, which would be much quicker, more effective in terms of labour and processing cost, and should produce a larger and better quality woodchip. Essentially, the higher cost of hiring larger scale machinery options could be overcome by teaming up with neighbouring farms.

This method of hedgerow management and woodfuel generation presents opportunities for co-operative ventures between farmers and farmers, farmers and local community groups or between farmers and local woodfuel users such as schools. There are an endless number of possibilities, where farmers could allow local community or volunteer groups to manage their hedges for them (by coppicing them for woodfuel) in exchange for the wood they harvest, or sub-contract out the management of their hedges to a local agricultural or community woodfuel contractor. This harvested wood could be divided amongst the group for their own use, sold on the open market either as firewood or woodchip, or provided to the rural fuel-poor, many of whom are vulnerable elderly people. There are several examples in the south west of England in particular where innovative community groups are making use of their local woodfuel resources (NAAONB 2013).

Alternatively there is potential for farmers to diversify their core farm business, making full use of the resources they have on-farm e.g. space, concrete yard, barns, tractor and trailer, front end loader and grain bucket, chainsaw, and potentially quiet months in the winter. There are opportunities for farmers either to become the hedge management or hedgerow woodfuel contractor, producing and selling timber locally either as firewood logs and/or woodchip, supplying local domestic users or schools and offices with woodfuel boilers, or establishing themselves as a woodfuel hub, providing a facility where other local farmers can take their timber resources for processing; a collection and distribution point which overcomes the problems associated with small-scale production.

Case study: Racedown Farm firewood business, Dorset

Ross and Ewan Dickenson, farmers in Dorset have diversified their farm business and established a local firewood enterprise based on their farm. They gave up dairy farming, like many others, and now have beef cattle, but in the winter months particularly they focus on their firewood business.

They coppice the hedges on their farm for firewood, as well as those on neighbouring farms within 3km, which generates approximately 40% of the firewood they sell. Another 40% they harvest from local woodlands and they buy in 20% from other woodland contractors. They process, bag and sell their firewood from the farm, selling to local customers usually within 5km of the farm. It is their policy to keep the margins small and the price of their firewood down to counter the high rural fuel poverty locally.

Local land owners and farmers pay Ross and Ewan Dickenson to coppice their hedges, who get to keep the cordwood and sell it at the farm gate as firewood. The farmer has his hedge rejuvenated and doesn't need to flail it every year, so he saves money. It's a win-win situation for everyone.

These sorts of enterprises are ideally suited to being locally based, minimising transport costs and therefore firewood prices and providing much-needed rural employment. As the whole of Ross Dickenson's business operates within a 5km radius, the potential for businesses of this kind and scale across the whole of the country is significant.

Case study: Odiham woodfuel hub, Hampshire

Odiham woodfuel hub based on Down Farm near Hook in Hampshire is owned and run by Robert Benford, a farmer who owns and works Down Farm. It is one of two woodfuel hubs operated by the Hampshire Woodfuel Co-operative. He has diversified and set up a woodfuel hub and waste recycling facility where green and brown landscaping waste is taken in at a price, sorted and processed into logs, biomass woodchip and green chip for composting instead of contractors having to pay for it to go to landfill. Nothing is wasted; even the shards from the huge woodchip screen are sold as kindling. They also accept and buy in forestry material for processing into biomass woodchip, so it provides a one-stop shop for all those working in the landscaping and forestry sectors producing plant residues. There was obviously a need for such a facility not met by local authority recycling facilities in the area. The woodchip is then sold through the Hampshire Woodfuel Co-operative to community heating schemes, schools, large houses and glasshouses as an alternative, competitively- priced source of fuel where mains gas is not available. For further information about the farm and the woodfuel hub, see www.downfarmodiham.co.uk.

7. Conclusions and recommendations for harvesting woodfuel from hedgerows

It should be noted that all the conclusions and recommendations drawn here are based solely on the results and experiences gained from the two hedgerow harvesting machinery trials carried out by the Organic Research Centre at Elm Farm and Wakelyns Agroforestry in 2014-2015.

Planning and preparation

- Ideally hedges should be coppiced between October and February, after leaf fall and before the bird nesting season. Hedges should only be coppiced outside of this window in September, March or April when restricted by ground conditions, and processes should be put in place to minimise the disturbance to wildlife.
- When planning the management of hedges by coppicing, the ground conditions and access to the hedges need to be taken into consideration. Compaction and rutting of the ground should be avoided wherever possible, though this is more important in grassland which is not so easily ploughed out and re-sown as arable land. The route which coppicing and chipping machinery will take needs to be carefully planned to minimise cross-field tracking and impact, especially if carried out in winter, when soils are soft and vulnerable.
- It may not be possible to coppice some hedges between October and April by any means other than manual fell if the ground becomes very wet over the winter, perhaps because it is low-lying, poorly drained or on a slope. A man with a chainsaw can walk in to most sites to coppice them, though the coppiced timber may need to be left *in situ* to be moved and processed with the aid of machinery when the ground dries out in the spring. These hedges could be coppiced in September or April, but there are disadvantages to both, with leaves still on hedges or nesting birds respectively.
- It is important to allow enough time when planning hedgerow coppicing works, to ascertain which regulations need to be complied with and which permissions and licences are required. Information on stem diameter, timber volume, TPOs and EPS etc then needs to be gathered together, and the hedgerows selected to be coppiced may need to be changed in light of the findings. Allow sufficient time when planning hedgerow coppicing works to get all the necessary permissions and licences in place before the contractors arrive to start the hedgerow coppicing work.
- To prepare a hedge for coppicing, fence removal and cutting back of outgrowth may be required. Some mechanised coppicing options, for example manual fell with chainsaw or machines with a good reach such as tree shears or felling grapple with chainsaw bar may be able to carry out coppicing without needing to remove external fences. However, it is important to remove all wire, such as old fencing, from inside the hedge before coppicing and chipping to ensure machinery is not damaged and the blades blunted. It may also be easier to coppice a hedge once its outgrowth has been cut back. Where outgrowth has grown through fences, cutting it back to the fence will aid the removal of the fence, and further cutting back may then be required.
- Try to synchronise fence replacements with the coppice rotation. Once a hedge has been brought into a coppice rotation, replacement of the fence will likely coincide with the next coppice, the lifespan of timber fence posts being approximately 15 years. This will help to reduce the costs of fence removal and replacement. Coppice those hedges with the oldest fences most in need of replacing first.
- The trial organiser needs to make sure that public liability insurance and risk assessments are in place to cover trial staff, contractors and visitors before any trials take place. It is important to obtain copies of contractors' public liability and professional indemnity insurances, operators' qualifications and certificates, and risk assessments for their work. It is also important to clarify

the liability for any damage to machinery during trials, for example from falling material or metal present within timber material being coppiced or chipped.

Choosing the appropriate machinery

- It is important to match harvesting and chipping options to the nature and length of hedge to be coppiced. The rate of hedgerow coppicing will be dependent on the mean diameter and volume of the hedgerow material, the proportion of large diameter trees, and the quantity of work to be done, as well as the machinery used.
- Where possible use local machinery which can be driven to the hedge management site, and if using machinery that requires being transported with a low loader, make sure that there is sufficient work for it to justify the extra haulage costs. This should be at least one whole day's work, but could perhaps involve collaborating with neighbouring farmers to jointly hire machinery to carry out several small jobs in one locality, though a tracked machine will have to be moved by low loader even for very short distances along a road.
- It is always worth hiring experienced machine operators and chainsaw fellers who are ideally used to working with hedges or are otherwise familiar with coppicing and chipping small diameter material. These contractors are likely to be more confident and therefore more positive about the work, and are likely to deliver a better result and possibly a higher quality coppice cut and woodchip.
- Both the hydraulic tree shears and felling grapple with integral chainsaw options are likely to be better suited to large diameter single-stemmed material. Single blade circular saws are optimally designed for small diameter material or hedges which are less than 5m in height. The assisted fell and manual fell methods have the flexibility to work on most sites and hedges, because the chainsaw has the manoeuvrability to cope with the contours of coppice stools or hedgebanks. The manual fell method is however not suitable where there are large single-stemmed trees or where the hedge is more than approximately 5m tall, whereas the assisted fell method can handle pretty much all sizes of timber material.
- Assisted fell is a very quick and effective felling method, making best use of both manual and mechanised felling techniques, with the excavator able to take the brunt of the physical work in extracting and moving the hedgerow material as full length stems ready for processing, but demands a very experienced team who are used to working together because of the health and safety concerns of this coppicing method. Assisted fell and large chipper was found to be the most cost-effective harvesting and processing combination of all the machinery methods trialled when at least 280m of hedge was coppiced.
- Use coppicing methods which use a chainsaw blade, such as manual fell, assisted fell and the felling grapple with integral chainsaw to give a clean-looking coppice cut which is thought to minimise disease ingress.

Processing hedgerow material

- Use a large crane-fed chipper wherever and whenever possible, even if this means sharing the greater hire cost with a neighbour in a collaborative chipping job, because it is so much easier and quicker to extract, move and chip the hedgerow material than using a manually-fed chipper, especially if it has been left in the field to dry for a few months. Coppiced hedgerow material could be left *in situ* until enough material has been accumulated to warrant the use of a large scale chipper or neighbouring farms could share the cost between them.
- Due to the high proportion of twiggy material with a high percentage of bark, hedgerow woodchip will likely have a higher ash content than roundwood woodchip from forestry operations. Removing cordwood from coppiced material before chipping is therefore likely to negatively impact the quality of the woodchip produced and further increase the ash content. Hedgerow woodchip may also contain a higher percentage of fine material and long shards or slithers.

- These trials have demonstrated that woodchip of reasonable quality which meets industry standards (P16B and G30 grades under BS EN and ÖNORM woodfuel standards respectively) can be produced from whole-tree hedgerow material, whether it is produced by disc or drum chippers and whether the material is chipped green or dry. It is however important that the woodchip is matched to the right woodfuel boiler able to cope with the variable nature of hedgerow woodchip, such as fines, shards and higher ash content.
- The most favourable storage method trialled was to air-dry hedge material in field and chip it after 3.5 months drying, producing clean woodchip of 28% MC. If it is sold straight from farm gate, then there would be no storage or extra handling costs.

Economics of producing woodfuel from hedges

- Because every hedge is different, it is difficult to draw general conclusions from the results and produce precise costs for the various elements of the process. Every hedge has to be assessed and managed on its own merits.
- Economically, it is better to use hedgerow woodchip produced on-farm than to sell it. However it has been demonstrated that there is a market for hedgerow woodchip to owners of larger woodfuel boilers or woodfuel hubs of £18-20/m^3 (£72-80/t or €99-110/t) at 30% MC and perhaps more.
- The unit energy cost of producing hedgerow woodchip ranged from 1.6 to 3.5 p/kWh depending on the machinery options and hedge type, and would seem relatively favourable when compared to the cost of other woodfuels (3.43-5.21p/kWh) and fossil fuels (3.5-8.33p/kWh) and electricity (12p/kWh) (Forest Fuels, 2015). Using woodchip from hedges on-farm could therefore not only incur savings from reduced flailing but also provide low cost energy, as well as rejuvenate hedges and support wildlife.
- Hedgerow flailing costs £0.88/m; over 15 years this amounts to £13.20/m. For a farm with 10 miles or 16.1km of hedges, where half are managed by coppicing for woodfuel and therefore 400m are coppiced every year, £29,880 could be saved in reduced flailing costs over 15 years, not including the potential cost savings from using the woodchip as fuel or the income generated from the sale of the woodchip.

Working together to make hedgerow woodfuel work

- Coppicing hedges to produce local woodfuel presents opportunities for co-operative ventures between farmers and farmers, farmers and local community groups or between farmers and local woodfuel users such as schools. Alternatively there is potential for farmers to diversify their core farm business and develop integrated sideline businesses making full use of their on-farm resources.
- Farmers are in a great position to establish woodfuel hubs, waste recycling facilities or local firewood or woodchip enterprises. These sorts of businesses are ideally suited to being locally based, minimising transport costs and therefore firewood and woodchip prices and providing much needed rural employment.
- As the harvesting of hedgerow woodfuel is likely to be relatively small scale and localised, the opportunities to reduce costs at every stage of the process by pooling resources and working collaboratively with neighbours, local farmers and woodchip users should be realised.
- Using local machinery and local contractors to coppice hedges, and finding local markets for the hedgerow woodchip is key to making this innovative industry work. Hedgerow woodchip is a low value high volume product, so minimising transport distances and haulage costs is essential to its success. Keep it local, keep it sustainable.
- If it is viable to operate a local subsidiary farm-based firewood business with a 5km radius, then imagine what potential there is for businesses of this kind and scale across the whole of the country, or across north west Europe!

In conjunction with this report, a shorter, easy to use best practice guide has been produced by the Organic Research Centre on the management and harvesting of hedges for woodfuel. This contains lots of information on the government initiatives and legal consideration surrounding hedgerow woodfuel, as well as guidance on managing hedgerows with wildlife in mind and recommendations on every aspect of producing hedgerow woodfuel. To obtain a copy of *A guide to harvesting woodfuel from hedges*, please go to the TWECOM project page on the Organic Research Centre website at http://tinyurl.com/TWECOM.

8. Limitations and future research

Every hedge is different and unique, in terms of size (height and width), woody shrub and tree species composition, density and age, stage of growth in the hedge management cycle, history of management, and when it was last coppiced or laid. They are also variable along their length for a whole host of reasons including: soil variation, slope, presence of invasive species such as elder, grazing and browsing. It is therefore very difficult to find hedges which are similar enough to be able to compare them directly, whether looking at coppicing time or coppice regrowth, and it can also be difficult making comparisons between different sections of the same hedge. Because replicates are difficult, it is difficult to draw definitive conclusions from the results and produce precise costs for the various elements of the process.

Hedgerow science seems therefore to be a much more indicative and iterative process than a precise science, where results for specific sites and case studies can be given, generalisations made and guidelines and recommendations offered, but on the understanding that every hedge has to be assessed and managed on its own merits. However, long term trials are essential to allow the accumulation of valuable data on both the logistics and impacts of hedgerow coppicing for woodfuel over the entire coppicing cycle. Ideally this would be done on a farm, in a number of regions of the UK to take into account variations in landscape characteristics such as hedgerow densities, soil type, climate and farming practices.

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10. Appendices

Appendix 1.

Machinery trial quantitative results – summary table

Machinery Description	Option trialled	Hedge	Minutes/meter	Meters/hour	Meters/day	STDEV	Day hire cost (£)	Haulage cost (£)
Hydraulic Shears	Excavator mounted Dymax 10”/250mm grapple tree shears with added accumulator or feller buncher functionality mounted on an 8 tonne Komatsu PC78-6 zero swing excavator. 1 man, 1 machine, 1 chainsaw	21	2.78	21.58	151.08	0.86	525	500
Hydraulic Shears + chainsaw finish	Excavator mounted Dymax 10”/250mm grapple tree shears with added accumulator or feller buncher functionality mounted on an 8 tonne Komatsu PC78-6 zero swing excavator. 1 man, 1 machine, 1 chainsaw	21	3.30	18.16	127.12	0.23	525	500
Timber grab with integral chainsaw	Excavator mounted Gierkink felling grapple GMT 035 with chainsaw cutting bar mounted on 5t Kubota excavator. 1 man, 1 machine	1	2.64	22.73	159.11	0.53	500	500

Single circular saw	Tractor mounted single circular saw attachment on hedge cutting arm, with second tractor and front-mounted fork. 2 men, 2 machines, 1 chainsaw	2	2.90	20.69	144.83		480	100
	Tractor mounted single circular saw attachment on hedge cutting arm, with second tractor and front-mounted fork. 2 men, 2 machines, 1 chainsaw	1	5.40	11.11	77.78		480	100
Manual fell	Motor manual extraction of cordwood for firewood logs; Man with chainsaw to separate brash from logs & prepare logs for firewood; brash to be chipped. Tractor with front mounted fork used to separate pile of hedgerow material	1	12.85	4.67	32.68	1.20	224	0
Assisted fell technique	Assisted fell technique; Motor manual felling supported by an 8 tonne Doosan DX80R excavator with a front-mounted 6'/1.8m land rake and Husqvarna 390 XP chainsaw with 24"/600mm cutting bar. 2 men, 1 machine, 1 chainsaw	21	1.58	37.97	265.82	0.29	450	150
Manual fell	Manual fell; Husqvarna 560XP chainsaw with 15"/425mm cutting bar. Two men and a chainsaw.	21	10.81	5.55	38.86	4.22	300	20

Appendix 2.

Woodchip quality results – summary table. WAF = Wakelyns Agroforestry; EF = Elm Farm

Site	Hedge	Material	Ash content (%)	Calorific content (MJ/Kg)	ÖNORM standard	BSEN standard	Moisture Content (%)
WAF	MF2	Brash only (10cm)	3.83	18.86	G30	fail	23.57
WAF	FG2	Brash only (economic)	2.42	18.99	fail	fail	23.08
WAF	CS2	All: chipped dry	2.52	19.06	N/A	N/A	21.41
WAF	FG1	All: chipped dry	2.93	19.41	G30	P16B	27.67
EF	21	All: chipped green	3.58	19.06	G30	P16B	30.58
EF	21	All: chipped dry	2.06	19.19	G30	P16B	25.17

Appendix 3.

Woodchip particle distribution results

Hedge 1 brash based woodchip (cordwood extracted down to an economical diameter):

Particle size						
Size	Specification	Result	Standard	Pass/Fail		
G30	>16mm	24.8%	<20%	Fail		
	2.8-16mm	68.7%	60-100%	Pass		
	<2.8mm	5.5%	<20%	Pass		
	<1mm	1.1%	<4%	Pass		
	Max length (cm)	0	8.5	Pass		
	Max area (cm2)	0	3	Pass	G30	Fail
	Number of shards	0		Pass		
G50	>31.5mm	1.5%	<20%	Pass		
	5.6-31.5mm	68.2%	60-100%	Pass		
	<5.6mm	29.2%	<20%	Fail		
	<1mm	1.1%	<4%	Pass		
	Max length (cm)	0	12	Pass		
	Max area (cm2)	0	5	Pass	G50	Fail
	Number of shards	0		Pass		
P16B	<120mm	0.0%	100%	Pass		
	>45mm	1.0%	≤3%	Pass		
	3.15-16mm	63.7%	>75%	Fail		
	<3.15mm	4.1%	≤12%	Pass	P16B	Fail
	Cross Sectional Area	0.0	1	Pass		
P31.5	<120mm	0.0%	100%	Pass		
	>45mm	1.0%	≤6%	Pass		
	8-31.5mm	71.6%	>75%	Fail		
	<3.15	4.1%	≤8%	Pass	P31.5	Fail
	Cross Sectional Area	0.0	2	Pass		
P45	<120mm	0.0%	100%	Pass		
	>100mm	0.0%	≤3.5%	Pass		
	>63mm	0.0%	≤6%	Pass		
	8-45mm	74.3%	>75%	Fail		
	<3.15	4.1%	≤8%	Pass	P45	Fail
	Cross Sectional Area	0.0	5	Pass		

Hedge 1 brash based woodchip (cordwood extracted down to an 10cm diameter):

		Particle size				
Size	Specification	Result	Standard	Pass/Fail		
G30	>16mm	15.5%	<20%	Pass		
	2.8-16mm	63.0%	60-100%	Pass		
	<2.8mm	18.9%	<20%	Pass		
	<1mm	2.6%	<4%	Pass		
	Max length (cm)	0	8.5	Pass		
	Max area (cm2)	0	3	Pass		
	Number of shards	0		Pass	G30	Pass
G50	>31.5mm	1.5%	<20%	Pass		
	5.6-31.5mm	47.1%	60-100%	Fail		
	<5.6mm	48.8%	<20%	Fail		
	<1mm	2.6%	<4%	Pass		
	Max length (cm)	0	12	Pass		
	Max area (cm2)	0	5	Pass		
	Number of shards	0		Pass	G50	Fail
P16B	<120mm	0.0%	100%	Pass		
	>45mm	0.0%	≤3%	Pass		
	3.15-16mm	60.4%	>75%	Fail		
	<3.15mm	15.2%	≤12%	Fail		
	Cross Sectional Area	0.0	1	Pass	P16B	Fail
P31.5	<120mm	0.0%	100%	Pass		
	>45mm	0.0%	≤6%	Pass		
	8-31.5mm	46.3%	>75%	Fail		
	<3.15	15.2%	≤8%	Fail		
	Cross Sectional Area	0.0	2	Pass	P31.5	Fail
P45	<120mm	0.0%	100%	Pass		
	>100mm	0.0%	≤3.5%	Pass		
	>63mm	0.0%	≤6%	Pass		
	8-45mm	47.4%	>75%	Fail		
	<3.15	15.2%	≤8%	Fail		
	Cross Sectional Area	0.0	5	Pass	P45	Fail

Hedge 21 chipped green:

Size	Specification	Result	Standard	Pass/Fail
		Particle size		
G30	>16mm	7.7%	<20%	Pass
	2.8-16mm	83.0%	60-100%	Pass
	<2.8mm	8.0%	<20%	Pass
	<1mm	1.3%	<4%	Pass
	Max length (cm)	0	8.5	Pass
	Max area (cm2)	0	3	Pass
	Number of shards	0		Pass
G50	>31.5mm	1.8%	<20%	Pass
	5.6-31.5mm	61.3%	60-100%	Pass
	<5.6mm	35.6%	<20%	Fail
	<1mm	1.3%	<4%	Pass
	Max length (cm)	0	12	Pass
	Max area (cm2)	0	5	Pass
	Number of shards	0		Pass
P16B	<120mm	0.0%	100%	Pass
	>45mm	1.6%	≤3%	Pass
	3.15-16mm	77.5%	>75%	Pass
	<3.15mm	6.3%	≤12%	Pass
	Cross Sectional Area	0.0	1	Pass
P31.5	<120mm	0.0%	100%	Pass
	>45mm	1.6%	≤6%	Pass
	8-31.5mm	56.8%	>75%	Fail
	<3.15	6.3%	≤8%	Pass
	Cross Sectional Area	0.0	2	Pass
P45	<120mm	0.0%	100%	Pass
	>100mm	0.0%	≤3.5%	Pass
	>63mm	1.6%	≤6%	Pass
	8-45mm	58.7%	>75%	Fail
	<3.15	6.3%	≤8%	Pass
	Cross Sectional Area	0.0	5	Pass

G30	Pass
G50	Fail
P16B	Pass
P31.5	Fail
P45	Fail

Hedge 21 chipped dry:

Particle size				
Size	Specification	Result	Standard	Pass/Fail
G30	>16mm	15.5%	<20%	Pass
	2.8-16mm	76.4%	60-100%	Pass
	<2.8mm	7.5%	<20%	Pass
	<1mm	0.7%	<4%	Pass
	Max length (cm)	0	8.5	Pass
	Max area (cm2)	0	3	Pass
	Number of shards	0		Pass
G50	>31.5mm	2.5%	<20%	Pass
	5.6-31.5mm	62.9%	60-100%	Pass
	<5.6mm	33.9%	<20%	Fail
	<1mm	0.7%	<4%	Pass
	Max length (cm)	0	12	Pass
	Max area (cm2)	0	5	Pass
	Number of shards	0		Pass
P16B	<120mm	0.0%	100%	Pass
	>45mm	1.1%	≤3%	Pass
	3.15-16mm	78.0%	>75%	Pass
	<3.15mm	4.0%	≤12%	Pass
	Cross Sectional Area	0.0	1	Pass
P31.5	<120mm	0.0%	100%	Pass
	>45mm	1.1%	≤6%	Pass
	8-31.5mm	73.3%	>75%	Fail
	<3.15	4.0%	≤8%	Pass
	Cross Sectional Area	0.0	2	Pass
P45	<120mm	0.0%	100%	Pass
	>100mm	0.0%	≤3.5%	Pass
	>63mm	0.8%	≤6%	Pass
	8-45mm	76.7%	>75%	Pass
	<3.15	4.0%	≤8%	Pass
	Cross Sectional Area	0.0	5	Pass

G30	Pass
G50	Fail
P16B	Pass
P31.5	Fail
P45	Pass

Hedge 1 all hedge material chipped (dry):

Particle size				
Size	Specification	Result	Standard	Pass/Fail
G30	>16mm	13.9%	<20%	Pass
	2.8-16mm	76.2%	60-100%	Pass
	<2.8mm	7.8%	<20%	Pass
	<1mm	2.1%	<4%	Pass
	Max length (cm)	0	8.5	Pass
	Max area (cm2)	0	3	Pass
	Number of shards	0		Pass
G50	>31.5mm	0.7%	<20%	Pass
	5.6-31.5mm	64.3%	60-100%	Pass
	<5.6mm	32.8%	<20%	Fail
	<1mm	2.1%	<4%	Pass
	Max length (cm)	0	12	Pass
	Max area (cm2)	0	5	Pass
	Number of shards	0		Pass
P16B	<120mm	0.0%	100%	Pass
	>45mm	0.0%	≤3%	Pass
	3.15-16mm	79.7%	>75%	Pass
	<3.15mm	7.2%	≤12%	Pass
	Cross Sectional Area	0.0	1	Pass
P31.5	<120mm	0.0%	100%	Pass
	>45mm	0.0%	≤6%	Pass
	8-31.5mm	59.6%	>75%	Fail
	<3.15	7.2%	≤8%	Pass
	Cross Sectional Area	0.0	2	Pass
P45	<120mm	0.0%	100%	Pass
	>100mm	0.0%	≤3.5%	Pass
	>63mm	0.0%	≤6%	Pass
	8-45mm	59.9%	>75%	Fail
	<3.15	7.2%	≤8%	Pass
	Cross Sectional Area	0.0	5	Pass

G30	Pass
G50	Fail
P16B	Pass
P31.5	Fail
P45	Fail

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