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Making hedgerows pay their way: the economics of harvesting field boundary hedges for bioenergy

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Abstract Existing landscape features, such as field boundary hedgerows, can contribute to food, fodder, material, and energy production for an EU bio-based circular economy. Recent trials undertaken by the project team in the UK demonstrated that hedgerows can be managed to produce woodfuel of a quality that meets industry standards. However, to be attractive to farmers, woodfuel production from hedgerows must be profitable. This paper uses the FarmSAFE model to undertake a financial assessment with data generated from these trials. The net present value of a standard hedgerow management method (flailing every 2 years) was compared with those from alternative hedgerow management scenarios for woodfuel production over a 60 year time horizon. Using data from the hedgerow trials, the results showed that coppicing hedgerows for woodfuel production could provide a profit to the farmer. The sale of woodchips into an off-farm market was found to be profitable if harvesting with tree shears (medium scale harvesting capacity) or a Bracke felling head (large scale harvesting capacity), but chainsaw harvesting (small scale harvesting capacity) was unprofitable. When considering the use of woodchips on farm to replace purchased woodchip or heating oil, the financial benefit to the farmer increased. Sensitivity analyses showed that the use of medium scale machinery (tree shears) made the hedgerow enterprise most resilient to changes in prices, grants, and costs. This scale of machinery is appropriate for local energy production whilst also being affordable to farmers and local contractors.

Keywords Woodfuel · Coppicing · Agroforestry · Greenhouse gas emissions · Biodiversity

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Introduction

As world population increases, there is growing pressure to increase food, fodder and energy production on agricultural land to meet demand (TEEB 2010). Whilst innovative solutions that contribute to these multiple land-use objectives without adverse impacts on the environment need to be found (European Commission 2017), use of existing landscape features, such as hedgerows, can also contribute significantly to food, fodder, material, and energy

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production to help develop a bio-based circular economy in the EU (Ghaley and Porter 2013). Across much of Europe, hedgerows are an important part of our joint cultural heritage. Hedgerows cover a total of 1.78 million hectares in the EU, about 0.42% of the territorial area, with the largest areas found in France (598,000 ha), the UK (240,000 ha), and Italy (168,000 ha) (den Herder et al. 2016).

Hedgerows have traditionally been regarded as multi-functional, established mainly to improve the husbandry of livestock, prevent damage to arable crops, and mark property boundaries, whilst also providing food, materials and firewood (Baudry 2000). Today they are largely valued for their wildlife and landscape benefits and for the wide range of ecosystem services they provide, including regulation of water quality and quantity (Wolton et al. 2014) and crop pest control (Ricci 2009). These contributions to ecosystem services are recognised by policy makers, with hedgerow maintenance, conservation, creation, and restoration supported by several mechanisms within the EU Common Agricultural Policy (CAP). These range from compulsory protection of existing features through 'cross compliance' regulations and 'greening' options in Pillar 1 of the CAP, to various measures within Pillar 2 that member states can choose whether to implement or not. For example, within the 2014–2020 Rural Development Programme (RDP), 75 measures promote the maintenance, creation, and restoration of hedgerows (Mosquera-Losada et al. 2016).

Despite this support, many hedgerows are in decline, either through under-management, mismanagement or removal. Estimates of hedgerow loss across Europe since the 1950s range from 50 to 80% (Reif et al. 2001). The main threat to hedges and the services that they provide are changes in management practices related to agricultural intensification and a reduction in the perceived value of hedges to farmers (Oreszczyn and Lane 2000). In the UK, the majority of hedges that are still actively managed are flailed repeatedly at the same height, which eventually creates gaps and leads to a decline in hedge condition. Those hedges left unmanaged ultimately develop into lines of trees. The results of both over and under management are detrimental to the structural integrity of hedgerows (Garbutt and Sparks 2002). Hedges need periodic rejuvenation, either through coppicing or hedgelaying. However, these management options are costly, time consuming, and thus, often ignored. In light of this, a key question is therefore to determine whether it is possible to manage hedgerows as a productive part of the farming system to offset the cost of management, whilst using hedgerow management practices that maintain their cultural, biodiversity, and environmental values.

Trials in the UK and France have investigated the potential of using biomass from hedgerow management activities for local energy production as a way of supporting the rejuvenation of old hedges, restoring not only their economic role, but also their value to the wider landscape (Chambres D'Agriculture Bretagne, 2006; Wolton 2012). The trials compared hedge-laying techniques, where stems of the hedge are partially cut through and bent back into the hedge, with coppicing where hedges are cut near the base of the stems and removed. Coppicing combined with whole tree wood chip production was found to be the most cost-effective management technique for woodfuel production (Chambres D'Agriculture Bretagne 2006). Recent trials in the UK built on this work and assessed the feasibility of mechanising the process of coppicing hedges and chipping the resulting biomass, and demonstrated that hedges can be managed to produce woodfuel of a quality that meets industry standards (Westaway et al. 2016). However, to be attractive to farmers, the management of hedges for bioenergy must be profitable. This paper therefore develops a financial assessment of the UK trials using the FarmSAFE model (Graves et al. 2006, 2011) to undertake discounted cash flow analysis. It hypothesises that hedgerows can be managed to provide a profitable bioenergy enterprise for the farm and examines a number of scenarios. Costs associated with a standard hedgerow management method by flailing every two years were compared with hedgerows managed on a 15 year coppice rotation over a 60 year time horizon. A 15 year rotation was chosen as previous hedge biomass trials found that the best results in terms of biomass output and economics were obtained when hedges were coppiced at 6–7 m high with some stems more than 15 cm diameter; most UK hedges are mixed species and, depending on species, this diameter is reached within 8–20 years (Wolton 2012). Different management scenarios were compared including coppicing using: (1) small scale machinery (chainsaw); (2) medium scale machinery (tree shears), and; (3) large scale machinery (Bracke felling head). The impact of excluding or including available hedgerow grants was also examined. Lastly, the effects of different energy prices were assessed assuming that woodchips could be: (1) sold off-farm into a local energy market; (2) used on-farm as a substitute for buying woodchips, or; (3) used on-farm as a substitute for heating oil.

The analysis also examines the impact of upscaling coppice management to a local and national scale to determine to what extent hedgerow bioenergy could replace the use of fossil fuels to reduce GHG emissions. The UK's Committee on Climate Change has recently recommended a new ambitious emissions target for the UK to achieve net-zero greenhouse gases by 2050 (Committee on Climate Change 2019). Developing the capacity for low-carbon energy is part of the solution to meeting this new target and biomass production is recognised as one approach to reducing emissions. Afforestation targets set by the CCC have not currently been met and using the existing hedgerow network for bioenergy production could reduce this need for land use change whilst meeting the need for low-carbon energy production.

Materials and methods

Hedgerow harvesting machinery trials were carried out at two farms in England, Elm Farm and Wakelyns Agroforestry, during the winter of 2016/17 as part of the EU SustainFARM project (www.sustainfarm.eu, FACCE Surplus). The aim of these trials was to assess the feasibility, efficiency, costs, and viability of mechanising the process of coppicing hedges and processing the resulting hedgerow biomass as a local and sustainable source of woodfuel. Machinery and methods were selected to represent a range of machinery sizes, cutting mechanisms, work rates, and costs. These trials then provided the data that were used in the FarmSAFE model to undertake the financial analysis.

Site and trial descriptions

Elm Farm is an 85 ha organic livestock farm in the south east of England (Newbury, West Berkshire (51.23°N; 1.24°W)). The farm has an average annual rainfall of 670 mm, and an average annual temperature of 10.7 °C. The soil is mainly Wickham Series clays, which are poorly drained clay loams susceptible to structural damage. There are 45 separate hedges on the farm with a total length of approximately 9.5 km. However, these had not been actively managed for a number of years, apart from occasional side flailing to maintain field sizes and statutory roadside management. The hedge selected for coppicing in December 2016 measured 250 m in length and was a tall, dense roadside hedge on the western side of a single-track road, predominantly consisting of mature hazel (*Corylus avellana*) coppice stools, with some blackthorn (*Prunus spinosa*) out-growth. Tree rings of the coppiced stools were counted and indicated that the hedge was last coppiced around 20 years ago. Although the side of the hedge facing the road has been side flailed annually, recent management has been minimal, leaving the hedge to become large and overgrown, on average about 6 m in height and 3–5 m wide. The hedge was coppiced by a 3-man team from a local contractor using a chainsaw (Fig. 1a), cutting the stems at a height of 10–20 cm to allow new wood to regrow. One hedgerow tree every 50 m was marked and left to grow into a mature tree. The cut material from the hedge was chipped immediately using a Schleising 220 mx (6″) and a Bandit 120LD (12″). Both chippers were self-propelled, small, light, and manoeuvrable but hand fed and limited in the size of material they could handle.

Wakelyns Agroforestry is a diverse 22.5 ha organic silvoarable agroforestry farm in eastern England (near Diss, Suffolk (52.36°N 1.36°E)). Average annual rainfall for the area is 606 mm, and average annual temperature is 9.9 °C (Met Office East Anglia 1971–2000 averages). The soil type is clay loam over chalk. The 3.7 km of boundary hedges are a mixture of species. The trial at Wakelyns Agroforestry was carried out in January 2017 on an unmanaged mature mixed species hedge, with an average height of 7 m, a width 3 m, and a central ditch. The main species were hawthorn (*Crataegus monogyna*), field maple (*Acer campestre*) and willow (*Salix cinerea/caprea*). Tree ring counts indicated that the stems were last coppiced 21 years ago. Two types of machinery were trialled: 1) a 360 degree tree shear with a scissor action mounted on a 7.5 tonne excavator with a cutting capacity up to 35 cm, operated by a local hedge management contractor (Fig. 1b), and 2) a Bracke C16 felling head, an accumulating felling head with a circular saw cutting blade mounted on a purpose built Valmet 901.4

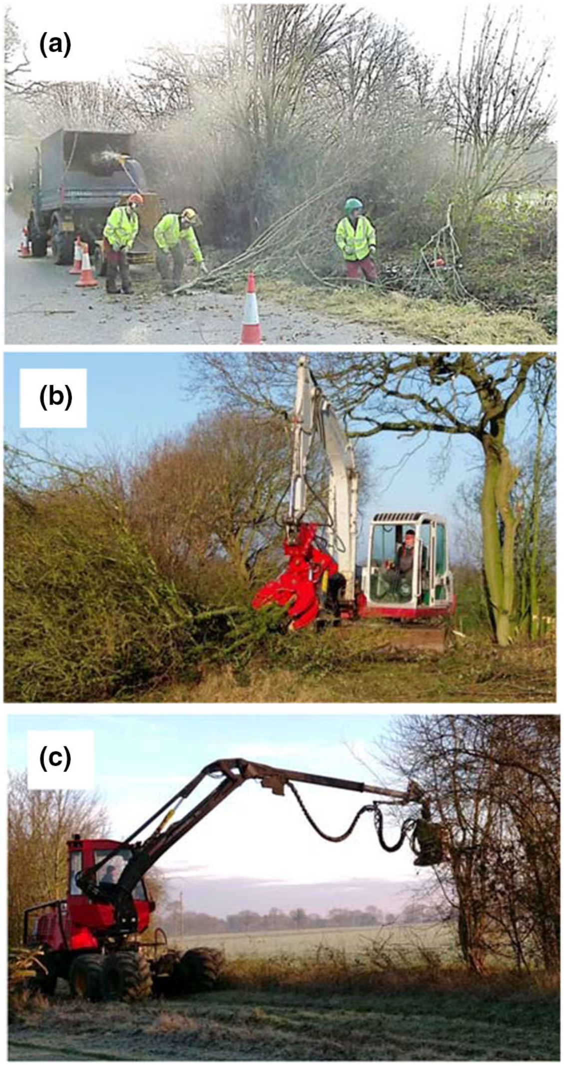


Fig. 1 Machinery used in coppicing trials in winter 2016/17: **a** chainsaw team at Elm Farm; **b** tree shears at Wakelyns Agroforestry; **c** Bracke felling head at Wakelyns Agroforestry

(Fig. 1c), operated by a national forestry contracting company. The cutting capacity was up to 260 mm and theoretically the Bracke left a cleaner cut than the shears. Each machine harvested continuously for 30 min and the length of hedge cut was measured to calculate efficiency. The Bracke felling head cut 24 m and the tree shears cut 9 m. The hedge material was stacked and left in the field to dry and then chipped in the summer of 2017 after approximately six months. A Jenz HM360 drum chipper was hired to chip the hedge material. This was a tractor-towed PTO-driven chipper with a telescopic crane feed, which could chip up to 300 mm diameter hardwood and had an integral 35 mm sieve as standard to produce G30 chips for fuel use.

Economic modelling of hedgerows

A financial analysis of the hedgerow scenarios was carried out using the FarmSAFE model (Graves et al. 2011). FarmSAFE is a plot and farm-scale model implemented in Microsoft Excel© that was developed during the SAFE project (2000–2004) to compare arable, forestry, and silvoarable systems. Whilst FarmSAFE was developed to evaluate farm enterprises on a per unit area basis, data inputs were adjusted here to generate outputs on a hedge length basis (units: £ 100 m^{-1} hedge).

Since the hedgerow coppice rotation was 15 years, the long-term costs and revenue were modelled using a discounted cash flow approach that could be aggregated to give the net present value (NPV) as the key criterion of evaluation. For this, the hedgerow was assumed to generate revenue in the form of woodchips and the generation of that revenue was assumed to impose management costs (*C*) including flailing, coppicing, and chipping costs. These operations were assumed to be undertaken on a contractor basis, and therefore here treated as costs that would scale with hedge length. In this respect, all labour, fuel, insurance, and machinery costs were embedded in the contractor charge and no additional costs were incurred by the farmer for hedge management. Costs, such as farm building maintenance for woodchip storage, were not included in the analysis, as these would not have varied between the different management scenarios. Whilst economic comparisons of annual systems such as arable crops can generally be undertaken on an annual basis, hedgerows, which are long-term perennial systems, need to be evaluated over many years, because revenue and costs are unevenly spread over time. In this situation, there is an opportunity cost to investing capital in the long-term, and a discount rate is typically used to aggregate all future revenue and costs into a NPV to reflect the opportunity cost of capital. A positive NPV indicates that the long-term value of the project is greater than the opportunity cost of capital and that it is worth investing in it for this reason. A negative NPV indicates that it is lower, and that it would be

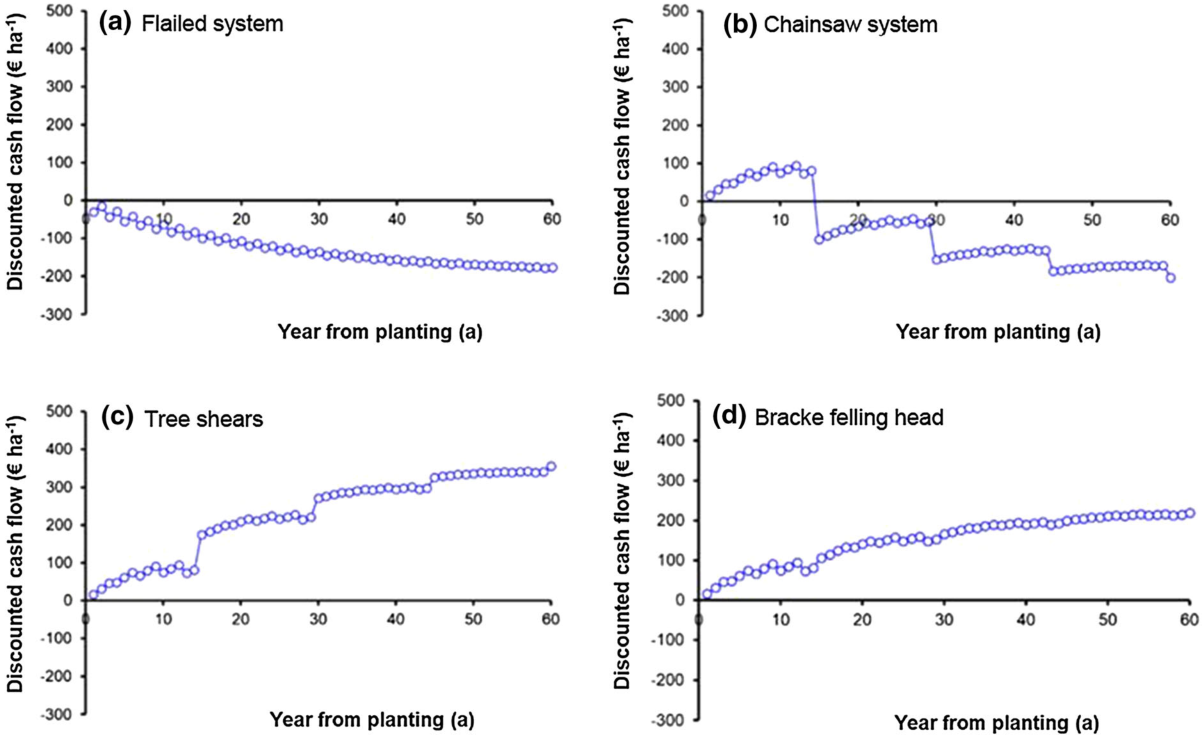


Fig. 2 Discounted net cash flow using a woodchip price of £7.59 m^3 and a discount rate of 4% over 60 years (£ 100 m^{-1}) for the flailed system (**a**), chainsaw system (**b**), tree shear systems (**c**), and Bracke felling head (**d**)

preferable, for example, to leave money in the investment, typically a bank, that provided the rate or return that was used as guidance for the discount rate. Here, the NPV (*NPV*; units: £ 100 m^{-1} hedge) was calculated as shown in Eq. (1):

$$NPV = \sum_{t=0}^{t=T} \frac{R_t - C_t}{(1+i)^t} \quad (1)$$

where R_t was the revenue from the enterprise, including any grants and subsidies, in year t (£ 100 m^{-1} hedge), C_t was the cost of management in year t (£ 100 m^{-1} hedge), i was the discount rate (typically in Europe set at 4%) and T was the time horizon (years).

The coppiced systems were modelled on a 15 year coppice rotation over a 60 year period, with side-trimming (four passes) every 3 years, starting from the fourth year after coppicing, when the re-growth needs cutting back. The different machinery types (chainsaw, tree shears and Bracke felling head) were compared to the counterfactual system of a standard large hedgerow representative of livestock farms, typically managed by trimming the sides and tops (in seven passes) every other year. A discount rate of 4% was used and the financial performance was calculated as a NPV over 60 years for a 100 m length of hedge, comparing three different prices for woodchips, with and without grants. Sensitivity analysis was performed to compare the impact of changes in discount rate, grants, prices, and costs for the different machinery types, using a woodchip value of £7.59 m^3 (i.e. the off-farm sale price).

The analysis doesn't include haulage costs for bringing the machinery to the site, the costs of preparation work needed to clear the hedges of old fence wires, or the capital costs of machinery or woodchip boiler installations. It also assumes the presence of an existing hedgerow network and therefore doesn't include the cost for establishing a new hedgerow.

Hedgerow revenue

Woodchips

Woodchip yield from the Elm Farm hazel hedge was 0.25 $m^3\ m^{-1}$ and from the Wakelyns mixed hedge was 0.28 $m^3\ m^{-1}$. Woodchip quality analysis found that all the hedgerow 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 30 mm in diameter, and therefore saleable on the open woodchip market. The material from Elm Farm was sold to Hampshire Woodfuel Cooperative, a local woodfuel co-operative, at £7.59 m^3 (net of storage, haulage and administration fee). At Wakelyns the woodchip was used on farm to fuel a woodchip boiler that heats the farmhouse. The "income" from this was interpreted in two ways: firstly, as the equivalent cost of buying in woodchips for use in an on-farm boiler at £21 m^3 (Hampshire Woodfuel Cooperative, 2017); secondly, as the cost of buying in the equivalent amount of heating oil at £34.80 m^3. This was calculated by obtaining the energy content of woodchips (857 kWh m^3 of woodchips) and multiplying this by the cost (£0.0406 kWh^{-1}) of heating oil (Energy Saving Trust 2017).

Hedgerow grants

In England, farmers can currently access grants for hedgerow management through the Rural Development Programme for England (RDPE) Countryside Stewardship grant scheme. Within the Countryside Stewardship Mid-Tier grant scheme, farmers can receive £16 100 m^{-1} for managing their hedges by cutting either no more than one year in three between 1st September and 28th February or no more than one year in two between 1st January and 28th February (Option BE3 (Natural England 2016)). There is also a capital grant available within the scheme that supports hedgerow coppicing at £4 m^{-1} (Option BN6 (Natural England 2016)).

Costs

Hedge trimming costs

The cost per pass was based on figures from four farms in Devon and West Dorset (Wolton and Dickinson, 2015 pers comm) which ranged from £0.14–£0.45 m^{-1}, for hedges requiring seven passes with rotary flail cutter to cut both sides and top. The average cost per pass was therefore calculated giving £0.0357 m^{-1}.

Hedgerow harvesting for woodfuel

Coppicing costs per metre were calculated by dividing the day rate with the number of metres each machine could cut in this time (based on a seven hour working day). Both the volume and mass of woodchips produced from each trial section of hedge were measured to give yield and costs on a per metre length of hedge, and per cubic metre of woodchip produced (based on an average of 0.25 $m^3\ m^{-1}$) (Table 1).

Scaling it up: farm-scale economics

To put the results in the context of energy production and use on a typical farm, Elm Farm and Wakelyns Agroforestry were used to illustrate the practical application of this approach. For Elm Farm, a woodchip boiler of 30 kW would be needed to heat the farmhouse, a five bedroom house typical of UK farms. This boiler requires approximately 30 tonnes of seasoned woodchips per year (105 m^3 of woodchips at a typical 30% moisture content). At Wakelyns Agroforestry, a Gilles 20 kW woodchip boiler which heats the farmhouse was already installed. This boiler requires 20 tonnes of seasoned woodchips per year (70 m^3 of woodchips at 30% typical moisture content). Based on these requirements the cost of woodchip production using the three machinery options was calculated and compared with the cost of using either bought-in woodchip or heating oil. Grant revenue (hedgerow and coppicing grants) for the length of hedge coppiced annually to meet the woodchip requirement was included in the calculations. The length of hedge needed to yield the woodchip on a continuous 15 year rotation was calculated.

Table 1 Revenue and costs associated with hedgerow management on a £ m^{-1} hedge and a £ m^3 woodchip basis

	£ m^{-1} hedge	£ m^3 woodchip
Revenue		
Hedgerow grant	£0.16	
Coppicing grant	£4.00	
Woodchip sale to woodfuel cooperative		£7.59
Equivalent woodchip purchase cost		£21.00
Equivalent heating oil replacement cost		£34.80
Costs		
Flailing (7 passes)	£0.25	
Chainsaw and chipping	£9.20	£36.80
Tree shears and chipping	£4.46	£17.80
Bracke felling head and chipping	£5.63	£22.50

Scaling it up: reducing UK GHG emissions

The UK Countryside Survey of 2007 recorded a total of 813,719 km in woody linear features. This includes hedges and lines of trees or shrubs—about 700,000 km in Great Britain (Carey et al. 2008) and 113,719 km in Northern Ireland (McCann et al. 2012). To consider the potential GHG emission reductions of replacing fossil fuels with bioenergy from hedgerows, we explored three scenarios: 10, 25 and 50% of the hedgerow network managed in a 15-year coppice rotation for woodchip production. Using the average woodchip yield from our trials, we calculated the kWh generated annually (using a conversion value of 857 kWh m^3 of woodchips), and the CO_2 equivalent saved (kg CO_2e) by replacing heating oil with hedgerow woodchip energy. The standard figure of 0.27652 kg CO_2e kWh^{-1} was used for heating oil (Department for Business Energy & Industrial Strategy 2019). Whilst woodchips are CO_2 neutral, other greenhouse gases such as N_2O and CH_4 which have not been absorbed from the atmosphere during growth are emitted, and woodchip combustion therefore has an emission factor of 0.01506 kg CO_2e kWh^{-1} (Department for Business Energy & Industrial Strategy 2019).

Results

The discounted cash flow (at a 4% discount rate) over 60 years for a woodchip price of £7.59 m^3 is shown in Fig. 2 for the flailed counterfactual system and the chainsaw, tree shears and Bracke felling head options. For the flailed system (Fig. 2a), the income from the annual hedge management grant (£16 100 m^{-1}) was not sufficient to offset the cost of management over the 60-year period and the NPV (−£177 100 m^{-1}) was negative (Table 2). Chainsaw harvesting led to a lower NPV (−£200 100 m^{-1}; Fig. 2b and Table 2), despite the additional coppicing grant of £400 100 m^{-1}, since the low work rate made harvesting costs relatively high. In comparison, the tree shears (Fig. 2c) and Bracke felling head (Fig. 2d) produced a profit over the 60-year period. In both systems, the cost of harvesting was offset by the revenue from the woodchip and grants, with the trees shears (NPV: £357 100 m^{-1}) found to be more profitable than the Bracke felling head (£219 100 m^{-1}) (Table 2).

Table 2 compares the benefit (at a 4% discount rate) of the flailed hedge counterfactual with the three different machinery harvesting systems for: (1) the off-farm woodchip sale price (£7.59 m^3); (2) the substitution value of the woodchips (£21 m^3) if they are purchased for use in an on-farm woodchip boiler, and; (3) the substitution value (£34.80 m^3) as a replacement for heating oil. This showed that as the value of the woodchips increased, the chainsaw system also became profitable, with a NPV of £194 100 m^{-1} at a woodchip value of £21 m^3 and a NPV of £599 100 m^{-1} at a woodchip value of £34.80 m^3. For the tree shears and Bracke felling head systems, the NPVs also increased considerably with the increase in woodchip value.

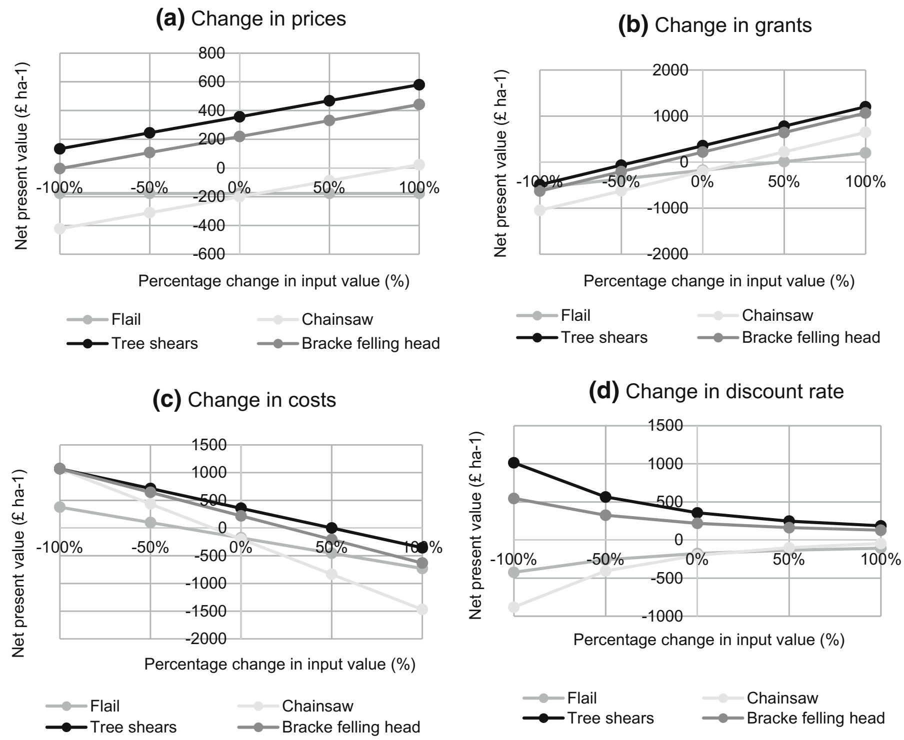
Table 2 The NPV at 4% discount rate for hedge flailing and three coppice hedge systems at three different woodchip prices over a 60-year period

	Flailed hedge (£ 100 m^{-1})	Coppiced hedge for woodfuel		
		Chainsaw (£ 100 m^{-1})	Tree shears (£ 100 m^{-1})	Bracke head (£ 100 m^{-1})
Discounted product revenue				
1. Assuming off-site sale (at £7.59 m^3)	0	223	223	223
2. Assuming substitution for woodchip purchase (at £21 m^3)	0	617	617	617
3. Assuming substitution for heating oil (at £34.80 m^3)	0	1022	1022	1022
Discounted grant revenue				
All systems	376	846	846	846
Costs				
All systems	553	1269	713	850
Net present value				
1. Assuming off-site sale (at £7.59 m^3)	− 177	− 200	357	219
2. Assuming substitution for woodchip purchase (at £21 m^3)	− 177	194	751	613
3. Assuming substitution for heating oil (at £34.80 m^3)	− 177	599	1156	1018

Sensitivity analyses

Sensitivity analysis on the effect of changing prices, grants, costs and discount rates was undertaken using an off-farm woodchip sale value of £7.59 m^3. The sensitivity analysis for changes in woodchip price (Fig. 3a) showed that the chainsaw system needed woodchip prices to increase by about 75% to achieve a positive NPV. For the tree shears and Bracke felling head systems, the sensitivity analysis on woodchip prices showed that even if the woodchip value dropped to zero, the systems would remain profitable due to income from the grants offsetting the cost of harvesting. The sensitivity analysis on changes in grant value (Fig. 3b) showed that removal of all grants resulted in all systems losing money, with the NPV dropping below zero when grants were reduced by around 50% for the tree shear system and 5% for the Bracke felling head system. Grants needed to increase by around 25% for the chainsaw system to break even, and 50% for the flailed hedge system to break even (this attracts only the hedge management grant of £16 100 m^{-1}). The sensitivity analysis for management costs (i.e. flailing, coppicing and chipping) (Fig. 3c) showed that the chainsaw system was the most sensitive to changes in costs, with a decrease in costs by around 15% leading to a break even NPV. If costs increased by 25%, the Bracke system became unprofitable, whilst for the tree shear system, this occurred when costs increased by 50%. The sensitivity analysis on the discount rate (Fig. 3d) showed that the flailed system and chainsaw systems always had negative NPV irrespective of the discount rate used here which varied between 0% (− 100%) and 8% (+ 100%) relative to the base discount rate of 4%. The NPV of tree shear and Bracke felling head systems, on the other hand, were profitable at all discount rates between 0 and 8%. Whilst lower discount rates decreased the profitability of the flailed system and chainsaw system even further, they increased the profitability of the tree shear and Bracke felling head systems. Conversely, as the discount rate increased, the NPV of the tree shear and Bracke felling head systems increased whilst the NPV of the flailed system and hedgerow system increased, although they remained negative.

Fig. 3 Sensitivity analyses to show the impact of changes in **a** prices, **b** grants, **c** costs, and **d** discount rate on the NPVs of the different machinery systems, using a woodchip price of £7.59 m^3



Scaling it up: farm-scale economics

The net benefit of using woodchip produced on farm in comparison with buying woodchips from an off-farm source or using heating oil to meet the energy needs of the farmhouses are shown in Table 3. At Elm Farm, the farmhouse required 105 m^3 of woodchip each year and the equivalent cost of heating oil to meet this energy need was £3,654 yr^{-1}. At Wakelyns Agroforestry, the farmhouse required 70 m^3 of woodchip

Table 3 Elm Farm and Wakelyns case studies showing the benefit of producing woodchips on farm compared with purchasing the woodchips from an off-farm source or purchasing heating oil to meet the energy needs of the farmhouses

	£ m^3	Elm Farm	Wakelyns
Woodchip boiler size		30 kW	20 kW
Woodchip boiler requirements		105 m^3 yr^{-1}	70 m^3 yr^{-1}
Cost of one year of heating oil equivalent	£34.80	£3,654.00	£2,436.00
Cost of one year of imported woodchip	£21.00	£2,205.00	£1,470.00
Cost of one year of woodchip by chainsaw	£36.80	£3,864.00	£2,576.00
Cost of one year of woodchip by tree shears	£17.80	£1,869.00	£1,246.00
Cost of one year of woodchip by Bracke	£22.50	£2,362.50	£1,575.00
Grant revenue for harvested hedge	£16.64	£1747.20	£1164.80
Net benefit versus heating oil			
Chainsaw system	£14.64	£1,537.20	£1,024.80
Tree shears system	£33.64	£3,532.20	£2,354.80
Bracke system	£28.94	£3,038.70	£2,025.80
Net benefit versus imported woodchip			
Chainsaw system	£0.84	£88.20	£58.80
Tree shears system	£19.84	£2,083.20	£1,388.80
Bracke system	£15.14	£1,589.70	£1,059.80

each year and the equivalent cost of heating oil to meet this energy need was £2,436 yr^{-1} (Table 3). The results showed that on farm production of woodchips using all three systems was more profitable than buying in woodchips or heating oil, with the tree shear system returning the greatest profit.

Assuming a 25 m^3 woodchip yield from 100 m of hedgerow, a length of 420 m of hedgerow would need to be coppiced every year to meet the needs of the Elm Farm boiler. Thus, on a 15 year harvesting rotation, a total length of 6.3 km of hedgerow would need to be in a coppice rotation to supply the required quantity of woodchips on a continuous basis. At Wakelyns Agroforestry, 280 m of hedge would need coppicing every year, with a total of 4.2 km required for a continuous supply of woodchips on a 15 year rotation. Elm Farm has 9.5 km of hedgerow so potentially could meet this requirement. Wakelyns Agroforestry has 3.7 km of boundary hedgerow, 1.5 km of twin rows of hazel short rotation coppice, and 2.2 km of twin rows of hazel short rotation coppice as alley cropping agroforestry, so could also potentially meet this need.

Scaling it up: reducing UK GHG emissions

Table 4 shows the results of scaling up hedgerow bioenergy production to the UK with scenarios of 10, 25 and 50% of the UK hedgerow network entering into a 15-year coppice rotation. The results show that there would be a GHG emissions reduction of 304, 760 and 1,520 Mt CO_2e at 10, 25 and 50% respectively. Agriculture accounted for 10% of UK GHG emissions in 2017 (Department for Business Energy & Industrial Strategy 2017) with a total of 45.6 Mt CO_2e. Assuming that 10% of the hedgerow network could be used to produce woodchips, woodfuel would reduce UK annual emissions from agriculture by 0.67%. Assuming that 25% of the hedgerow network could be used for woodchip production, the annual reduction would be 1.67% and assuming that 50% of the hedgerow network could be used for woodchip production, the annual reduction would be 3.33%.

Discussion

Is harvesting hedgerows for woodfuel financially profitable?

Harvesting boundary features such as hedgerows for woodfuel is common in other parts of Europe. In some areas of northern France, hedgerows are coppiced and still provide an important fuel source, producing 4.4 million cubic meters of fuel per year and accounting for 11% of the total firewood used by households in 1997 (Lofti A et al. 2010). In the UK, however, while the biodiversity and cultural benefits of hedgerows are well recognised, their potential as a productive component of the farming system has been all but forgotten. This study shows that it is financially viable to manage hedges for woodfuel by coppicing, with both the tree shears and Bracke felling head systems

Table 4 GHG emission reductions at 10, 25 and 50% of the UKs hedgerows being managed for bioenergy production

	Unit	% of woody linear features managed for woodchip bioenergy production		
		10%	25%	50%
Total UK woody linear features	km	813 719	813 719	813 719
Total in 15-year coppice rotation	km	81 372	203 430	406 860
Annual length coppiced	km	5 425	13 562	27 124
Annual woodchip yield	$m^3 \times 10^{\wedge 3}$	1 356	3 390	6 781
Annual energy generated by hedgerow woodchip	MWh	1 162	2 906	5 812
Annual emissions from hedgerow woodchip	Gg CO_2e	18	44	88
Annual emissions from heating oil equivalent	Gg CO_2e	321	804	1607
Emissions reduction by replacing heating oil with woodchip	Gg CO_2e	304	760	1520

returning a profit over the 60 year period when selling woodchips off-farm. When considering the use of woodchips on farm to replace purchased woodchips or heating oil, the cost savings make energy production from hedgerows even more financially attractive. The sensitivity analyses showed that the medium-scale machinery (tree shears) is the most robust to changes in prices, grants and costs. This scale of machinery suits local energy production scales since it can be more easily afforded by farmers and local contractors. In contrast, larger-scale machinery, such as the Bracke felling head, is more suitable for regional scales due to limited availability and the cost of haulage. Haulage adds a significant cost to harvesting operations and the decision as to when the large scale, more expensive equipment becomes cost effective, will in part be driven by the quantity of hedgerow that needs to be harvested and the distances that the machinery needs to be transported.

In this financial analysis, the chainsaw system was only profitable when considering woodchips as a replacement for purchased woodchip or heating oil. This was due to production costs being higher than the woodchip revenue and grants. However, these costs might be lower if using existing farm labour instead of contractors. The sensitivity analysis showed a decrease in management costs of around 15% would make the system break even. This could also provide employment opportunities for farm staff during quieter winter months. A major limitation on most farms is ground conditions and accessibility for machinery at the time of year that cutting and chipping needs to be carried out. Where ground conditions are liable to rutting or compaction by machinery, the lower impact chainsaw option may be more appropriate.

Our analysis shows that managing hedgerows for bioenergy provides the greatest benefit when the energy is used on farm to replace imported woodchip or heating oil, but this requires investment in a woodchip boiler and space to store the woodchip. These investment costs are not included in our analysis, nor are the establishment costs of planting new hedges included. In addition, our analysis does not take into account potential impacts on crop yields or animal production (positive or negative) of having taller hedges. Taller hedges may provide more shelter for animals and crops but towards the end of the rotation will reduce light availability for adjacent crops or pasture. Our farm-scale calculations demonstrate that it is theoretically possible to meet woodchip needs from on-farm resources for Elm Farm and Wakelyns Agroforestry, but it may not be advisable to bring all (or the majority) of the farm hedges into a coppicing rotation (see biodiversity considerations below). One solution to this may be to reduce the rotation length between coppicing. We based our calculations on a 15 year coppice rotation, but it may be possible to shorten this rotation, especially when there are predominantly fast growing species such as willow and hazel within the hedges. Further research is needed on re-growth rates of coppiced hedges to identify optimum coppice rotations.

Wider implications for biodiversity and carbon sequestration

There are concerns that managing hedges for woodfuel production by coppicing may conflict with other ecosystem services that hedgerows provide, in particular the impact on biodiversity and carbon storage. Change in management adopted on any scale has potential impacts and the introduction of coppice management to hedges for woodfuel is likely to have both positive and negative impacts on the wildlife of individual hedges and on biodiversity at a landscape scale. Potential impacts include an alteration of the hedge microclimate, changes in hedge structure, plant species composition, and landscape connectivity. Reduced connectivity between patches of semi-natural habitat may impact species that use the hedgerows as corridors, such as dormice (*Muscardinus avellanarius*) which have been found to be gap adverse (Bright 1998) and may be negatively affected by coppicing. As a general recommendation, it has been suggested that no more than half the hedges on a farm should be managed to produce a fuel crop, that no more than 5% of hedges should be coppiced in any one year, and that the coppice rotation should be no longer than 20 years (Wolton, 2012). In addition, mature hedgerow trees should be retained, especially those with veteran features.

A hedgerow's capacity to immobilize carbon increases with vegetation maturity (Borin 2010), width (Falloon 2004) and network density (Walter 2003). It is estimated by Falloon et al. (2004) to take five years for a hedge to reach its maximum carbon storage capacity and, assuming a representative hedgerow height and width of 1.5 m, an annual accumulation rate of one tonne of carbon per hectare can be attained. The carbon sequestration value of hedgerows is therefore dependent on their permanence and hedges require preservation if any carbon storage benefits are to be maintained (Falloon 2004). Rotational coppicing to ground level and using the resulting biomass for bioenergy production conflicts with the long-term aboveground storage of carbon in hedgerows. However, the carbon substitution value of replacing fossil fuels with renewable energy should also be considered, and our calculations show that hedgerow bioenergy can reduce greenhouse gas emissions and contribute in a small way to meeting UK government targets for net zero emissions by 2050.

An alternative use for woodchip from hedges that has more recently been increasing in interest is as a soil improver. This could be in the form of composted material, or alternatively applied fresh, a practice called ramial chipped wood (RCW). Early work carried out in Canada and the USA showed promising effects of RCW on soil biological activity and soil organic matter (Caron et al. 1998; Free 1971), and research is currently underway on farms in the UK to investigate the use of RCW from hedgerows as a soil improver (Westaway et al. 2019).

Conclusion

In conclusion, the financial analyses demonstrate that it is possible to manage hedges for bioenergy production, with the medium-scale machinery (tree shears) being the most robust to changes in prices, grants, costs and discount rate. This machinery scale suits local energy production scales because it can be afforded by farmers and local contractors. Even without grants, harvesting woodfuel from hedges is beneficial when used to replace fossil fuels for on-farm heat generation. The farm-scale analysis suggests that hedgerows could successfully provide fuel at a farm scale, although care should be taken to ensure that their multiple on-farm role is not compromised. At a national scale, it appears that hedgerow management could play a small but significant role in contributing to policy objectives for the reduction of GHG emissions from agriculture.

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Making hedgerows pay their way: the economics of harvesting field boundary hedges for bioenergy

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