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An assessment of road-verge grass as a feedstock for farm-fed anaerobic digestion plants

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ABSTRACT

Cuttings from road-verge grass could provide biomass for energy generation, but currently this potential is not exploited. This research assessed the technical, practical and financial feasibility of using grass harvested from road verges as a feedstock in farm-fed anaerobic digestion (AD) plants. The methane potential (191 mL CH_4 g_{DM}^{-1}) and digestion characteristics of verge grass were similar to those of current farm feedstocks; indicating suitability for AD. Ensiling had no significant impact on the biomethane generated. Testing co-digestions of verge grass with current farm feedstocks showed enhanced methane yields, suggesting that verge grass could be a valuable addition to AD feedstock mixes. In a case study of the UK county of Lincolnshire, potential volumes and locations of verge grass biomass were estimated, with capacities and locations of existing AD plants, to assess the potential to supply practical grass volumes. Grass harvesting costs were modelled and compared with other feedstock costs. Finally, the attitudes of AD operators to using verge grass were investigated to understand whether a market for verge grass exists. In a small survey all operators were willing to use it as a feedstock and most were prepared to pay over the estimated harvesting cost. If verge grass was legally recognised as a waste product it could be attractive to AD operators especially where financial incentives to use waste feedstocks are in place. In rural areas, verge grass could be harvested and co-digested by existing farm-fed AD plants, potentially reducing the cost of road verge maintenance and increasing biodiversity.

1. Introduction

In the UK there are over 270 000 km of rural roads and motorways [1,2]. The grass verges of these roads are cut regularly and the cuttings could provide an important bioenergy resource, but the value of this resource, and the practicalities of harvesting, have not been fully investigated. The aim of this research was to determine whether it could be practical to harvest road-side grass for digestion in farm-fed AD plants to generate some income for local authorities. The suitability of the grass as a replacement for current feedstocks was assessed by determining the methane potential and digestion characteristics of grass samples. A case study of the county of Lincolnshire in eastern England was used to understand whether practical volumes of grass were available near AD plants, whether the grass could be harvested at a cost which would make the process economically feasible, and whether AD plants were willing to use and pay for verge grass.

1.1. Verges

Road verges serve many practical purposes, including providing: space for pedestrians and horse riders, emergency areas for cars, access to utility infrastructure, lines of sight for motorists, road drainage and an

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attractive environment [3]. Mowing grass is mainly carried out to maintain visibility and safety; with aesthetics a less important factor [4]. Most UK local authorities mow their verges two or three times per year but some have reduced this to once a year [4,5]. Grass cuttings are generally left *in-situ* to decompose. Two or three cuts per annum are favoured by most local authorities and maintenance contractors as fewer cuts can result in longer and thicker vegetation which is harder and more expensive to cut [5]. Although verge grass is not actively managed, fertilisers from adjoining fields can leach in to the soil and sprayed herbicides can drift on to verge grass affecting yield and species mix. On roads which are salted in winter the verge composition is affected by salt spray which can inhibit some species and encourage salt tolerant plants [6].

Old rural road-verges are remnants of semi-natural grassland, used in the past for grazing livestock or for providing hay. The species present on a verge depend on the geology, soil, current management and previous land use, but most UK verges can be classified as type MG1 false oat grass *Arrhenatherum elatius* grassland, dominated by coarse grasses and tall herbs [7] according to the British Nation Vegetation Classification [8]. Verges on new UK roads are sown with a mixture of seeds approved by the UK Department for Transport and in accordance with national standards [9]. These mixtures generally contain *Festuca rubra* (creeping red fescue), *Lolium perenne* (perennial rye grass), *Poa pratensis* (smooth stalk meadow grass), *Festuca trachyphylla* (hard fescue), *Agrostis capillaris* (bent) and *Trifolium* (clover) [10,11].

Cutting grass and leaving the cuttings in place leaves a mulch which both smothers the plants below it and increases the nutrient level of the soil [7] which leads to decreased biodiversity due to competition. Removing grass cuttings will increase the range of species present in a verge [12]. Conservation groups have recognised the value of grass verges as linear conservation reserves. In the UK verge conservation projects have been operating in Lincolnshire [13], Powys [14], and Cumbria [15]. In Cumbria, the Council requests farmers to take a late hay crop from verges and avoid early-season mowing, to preserve species of wild flowers that have survived from ancient grassland and have been largely lost from intensively farmed fields [15].

The erosion of grass covered sea defence dykes can be improved by unfertilised haymaking on all soil types [16]. In Lincolnshire the drains and sea defences could be strengthened by grass cutting and harvesting, and this grass could be used for AD.

The potential yield of verge grass is dependent on many factors and is likely to vary significantly from year to year and site to site [17]. The species of plants, soil fertility, incidence of fertiliser run off and herbicide drift, the temperature, rainfall and management regime (i.e. the timing, and number of cuts and whether grass is removed), will all affect both the yield and moisture content of the grass harvested. The yield from a verge is also dependent on the distance from the road with yield increasing with distance from the carriageway [7] so a wider cut could have a higher yield than a narrow one.

1.2. Anaerobic digestion

Anaerobic digestion (AD) is the biological conversion of organic matter to biogas under oxygen-free conditions [18]. The biogas produced from AD is approximately 60% methane and 40% CO_2 with traces of contaminants. Biogas can be combusted to generate heat and/or electricity; it can also be upgraded to biomethane for use as a transport fuel or for injection into the national gas grid [19]. AD also produces a digestate; the material that is not converted into biogas. The digestate contains the majority of the nutrients in the feedstock and can be used as a bio-fertiliser.

AD was originally used in the UK for processing animal manures on farms and human waste in water treatment plants, but co-digesting crops with manures can improve the performance of digesters [20] and thus increase income from higher methane yields.

Feedstocks used include: energy crops such as maize grown specifically for digestion, grass silage, waste food from processing factories and agricultural by-products such as straw. The balance of feedstocks in a digester needs to be managed carefully to allow the microorganisms to adjust to the new conditions [21] and an operator may be unwilling to change the feedstock of a stable plant.

In the UK alone the number of farm-fed AD plants (digesting only agricultural feedstocks) has increased from 45 in 2013 [22] to 357 in 2019 [23] and now outnumber sewage-treatment and industrial AD plants. Worldwide, the production of biogas from AD is highest in Europe, followed by Asia and America [24]. In 2017 Germany had by far the most European agricultural AD plants (over 9000) with significant numbers Italy, France, UK and Sweden too [25]. In the US there were 282 agricultural AD plants in 2018 [26]. Although Europe leads the world production of biogas there are most AD plants in Asia and Africa AD, however many of these are constructed on a domestic scale and thus have a lower total output [24].

1.3. Verge grass as a feedstock

The use of verge grass as an AD feedstock has been investigated in Denmark [27], Wales [14,17], Germany [28], the Netherlands [29], Belgium [30], Croatia [31] and Lincolnshire [32]. All studies found that verge grass was suitable for digestion, but problems with available machinery, the safe operation of vehicles during harvesting and year to year variations in yields were encountered, and it was expected that financial subsidies may be needed to support harvesting [30]. The distance from harvesting to processing is a key factor in establishing economically viable processes for bulky, low energy density biomass such as grass. Salter [17] recommended using a large number of small AD plants harvesting from 20 km radius harvesting areas rather than a single plant harvesting from a 45 km radius area to minimise the transport distances for the grass and digestate. In contrast Meyer [27] concludes that centralised processing at larger plants may have sufficiently improved efficiency to overcome the longer transport distances. Using grass as a feedstock for AD was found to reduce CO_2 emissions compared with generation of heat and electricity from fossil fuels. Salter [17], found that using verge grass from principal and classified rural roads in England and Wales to generate biomethane for transport fuel could save up to 24 000 t of CO_2 per annum. Using verge grass instead of an energy crop can reduce CO_2 emissions from AD energy production as GHG emissions from cultivation and fertiliser use are avoided, although the level of reduction will depend on the specific crops replaced and any resulting land use changes.

To ensure a reliable, year-round supply of feedstock the grass is usually ensiled. Ensiling is a biochemical preservation method widely used in livestock farming which converts fresh crop into silage. Once the biomass is sealed under anaerobic conditions lactic-acid producing bacteria (LAB) proliferate. LAB ferment the most readily-available organic matter into lactic acid, which accumulates, to decrease the pH of the crop to around 4.0 [33]. The decreased pH prevents the growth of spoilage microorganisms, allowing the crop to be stored for a prolonged period of time [34].

Contamination of the vegetation and soils on road verges arises from a variety of sources. Road vehicles emit potentially toxic elements (PTE) and polycyclic aromatic hydrocarbons (PAH) from tyre and brake wear as well as from exhaust pipe emissions and they can accumulate as dust deposits on the roads and verges. Further contamination can arise from waste discarded by drivers (e.g. drinks cans and take-away food containers) and from road surface treatments and repairs (e.g. rock salt, bitumen). Some contaminants present can affect the performance of AD plant. Others can present risks to the quality and safety of resulting digestate. An assessment of the PTE and PAH contaminants in the road-verge biomass used in this study was undertaken in an associated investigation [35]. The conclusion of that study was that, while higher levels of contamination by PTE and PAH were found in road-verge biomass (compared to background levels), the levels were well below those which could cause concern for AD plant operators or for agricultural use of the digestate.

The Environment Agency (EA) regulates the operation of AD plants in the UK [36] and the spreading of digestate on land. It specifies types of waste that can be processed in a farm AD plant operating on a standard rules permit; this includes wastes from agriculture, horticulture, the dairy industry and forestry. Verge grass is not classified in EA waste regulations and so it is not currently a permitted feedstock unless a temporary exemption is agreed for feedstock and digestate use. New categories of waste must be approved by the EA Waste Panel with fees payable by the applicant.

1.4. Incentives for bioenergy generation in the UK

Most UK AD plants generate electricity and heat (combined heat and power (CHP)). Newer and larger plants may upgrade the biogas to biomethane before injecting into the natural gas grid, if they are close to an injection point. Feed-in tariff (FIT) payments were available for 20 year terms for small generators of electricity [37], but from early 2019 the scheme was closed to new entrants [38]. Renewable heat incentive (RHI) payments can be claimed for the use of heat from biogas combustion and for biomethane injected into the gas grid [39]. Sustainability criteria now require newer AD plants to source more than 50% of their feedstocks from wastes or residues to qualify for full FIT and RHI payments [40].

Biomethane compressed or liquefied for use as transport fuel receives tradeable renewable transport fuel certificates (RTFCs) under the Renewable Transport Fuels Obligation (RTFO) scheme. Fuels from feedstocks classed as wastes or residues receive double the number of RTFCs [41].

1.5. Research aims

The aim of this research was to assess the prospects of harvesting verge grass for digestion in farm-fed AD plants. For verge grass to be a suitable feedstock it would need to be suitable for digestion as a part of a mix of feedstocks, so the digestion characteristics of verge grass samples alone and as part of a feedstock mix were assessed. As AD feedstocks are often ensiled to allow year round processing, the impact on ensiling on digestion characteristics was assessed. A case study was used to understand the demand for grass, the potential supply and the cost of harvesting verge grass.

2. Material and methods

2.1. Lincolnshire CC case study

Lincolnshire is a county in the east of England and Lincolnshire County Council (LCC) is responsible for the maintenance of nearly 8000 km of rural roads [1]. Most of these roads have grass verges and there are a number of roadside nature reserves. LCC currently cuts their verges twice a year to a width of at least 1.1 m, leaving the clippings *in situ*. The first cut is scheduled for between mid-April and the end of May and the second one for September. LCC is under pressure to reduce costs and deliver value for money but reducing verge cutting would result in over-grown verges within a few years, causing a hazard for drivers and pedestrians. The long term cost of clearing verges populated by woody plants could be significant. Eventually the structure of the road edges could begin to deteriorate as larger plants and their roots encroach. LCC wished to investigate the potential for harvesting the verge grass for digestion at local AD plants and at the same time enhance the biodiversity of the road network.

Lincolnshire is an intensively agricultural area where there are already many farm-fed AD plants, which could use verge grass as a feedstock. The road verges of Lincolnshire are among the widest in England with an average width of over 3 m on each side of the road [4], and could be managed as grassland. There is also a network of open drainage channels contained by grass banks and sea defences in Lincolnshire which are potential sources of grass for digestion.

Initial investigations of the feasibility of the use of grass cuttings for digestion at six sites in Lincolnshire [32] found that the grass was suitable for digestion (subject to Environment Agency approval following further testing for contaminants) and that some income could be generated to offset maintenance costs.

In June 2016 a test harvest was undertaken by Lincolnshire County Council, Peakhill Associates and the Lincolnshire Wildlife Trust to harvest verge grass for digestion at Scrivelsby Farm in Lincolnshire. This arable farm has a four tank AD plant: two thermal hydrolysis tanks, one main AD tank and a digestate storage tank. The thermal hydrolysis tanks maintain the biomass at 51 °C for 24 h and 53 °C for a further 24 h. The main AD tank is maintained at 45 °C. Scrivelsby Farm digests a range of agricultural feedstocks, and was already digesting grass silage as a part of its feedstock mix, and generated electricity and heat (CHP) (capacity 499 kW). The digestate produced was spread on their own farm land as fertiliser. The test harvest was carried out using an imported harvester leased for the pilot. The farm uses the heat generated for drying grain and wood as well as heating homes and farm buildings.

In 2018 a full season pilot of harvesting was undertaken [42,43]. This project was managed by LCC and funded 50:50 by The Greater Lincolnshire Local Enterprise Partnership (LEP) and Lincolnshire Verge Harvesting Ltd (owned by three Lincolnshire farms including Scrivelsby Farm). The three farms all had similar AD plants and were interested in digesting verge grass. A bespoke harvesting system was developed by local agricultural engineering company Scott's Precision Manufacturing Ltd, see Fig. 1. This had a grass cutting head that sucked up the grass and then blew it into a trailer.

2.2. Collection of samples and biomass yield data

The June 2016 pilot harvest as detailed in Ref. [35], provided harvest biomass yields, machinery performance data and composite road-verge biomass samples from six sites across Lincolnshire, as shown in Fig. 2. The sites were selected to cover a range of road types and traffic volumes. Verge grass samples were labelled Sx/Hy.z, where x = site reference number, y = harvest number and z = swath number. For example, the sample code: S2/H1.1 refers to a verge grass sample harvested from site 2 (S2), as shown in Fig. 2 from the first harvest (H1) in (June 2016) and the from the first 1 m swath of verge cutting (H1.1). A single 1–2 kg sample was taken from the mixed bulk material for each site. A subsample was selected for laboratory analysis through coning and quartering according to BS EN ISO 14780:2017. Laboratory analysis was conducted in duplicate from the subsample, unless otherwise specified.

Fig. 1. Verge harvester showing cutting head and suction tube.

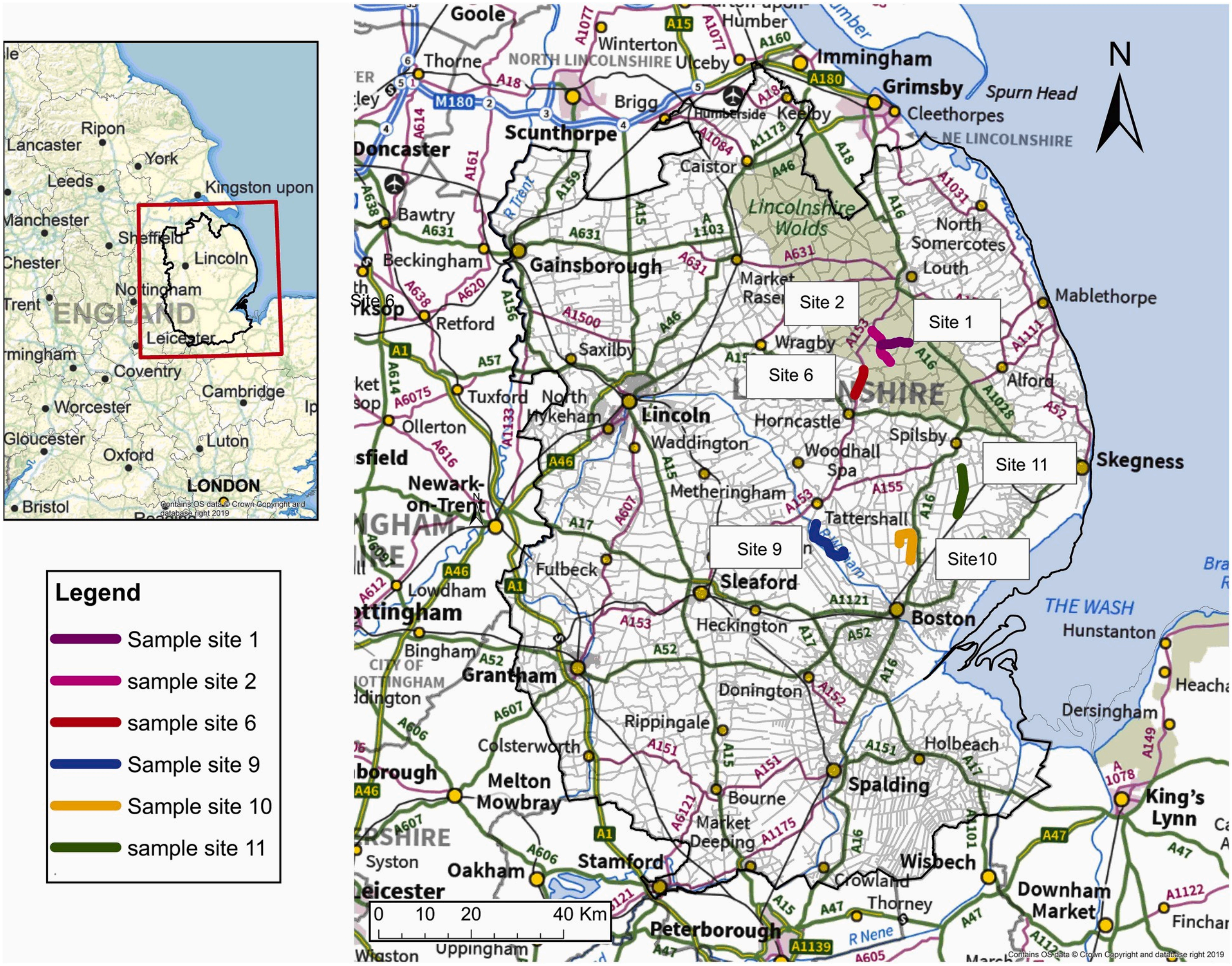

Fig. 2. Map of sample sites and location of Lincolnshire in UK (Base map from Ref. [44]).

The loaned harvester was assessed for suitability for full scale harvesting and a specification drawn up for an acceptable harvester for any future full scale grass collection. Fresh grass samples were stored at −20 °C. The remaining harvested grass was ensiled using on-site bale ensiling at Scrivelsby farm. No silage additives were used. Samples of ensiled grass were collected after 4 months and stored at −20 °C. Samples of farm feedstocks: maize, rye grass, straw, grass silage and chicken litter were also collected at Scrivelsby. Fresh inoculum was taken from the main AD tank, passed through a 1 mm screen to remove large particles and stored at 4 °C until required. Analysis samples were defrosted at ambient temperature for a minimum of 24 h and subsequently oven dried [Mermert drying oven] at 60 °C for a minimum of 24 h. The moisture loss was calculated through gravimetric difference. Samples of verge grass and farm feedstocks were homogenised through particle size reduction to <500 μm, using a cutting mill [Nutribullet].

In the 2018 project the biomass yield and harvesting performance data were recorded.

2.3. Analytical methods

Proximate analysis was determined according to BS EN ISO 18134–1:2015, BS EN 15402:2011 and BS EN 14775:2009, with fixed carbon calculated by difference. A SPEX 6770 Freezer Mill was used to reduce the particle size of samples to <150 μm for ultimate analysis. Ultimate analysis was determined according to BS ISO 17247:2013 using an EA112 Flash Analyser (CHNS), with oxygen calculated by difference.

Total solids (TS) and volatile solids (VS) were determined according to APHA (2005) using 1g for solid samples and 4 mL for hydrolysates. Equation (1) was applied to account for volatile losses in the grass silage [45].

$$\% \, VS_{Corrected} = 2.08 + 0.975 \times \% \, VS_{Uncorrected} \tag{1}$$

2.4. Biomethane potential tests (BMP)

Theoretical biomethane potential (BMP_{th}) was calculated from the elemental composition of the feedstocks applied to the Buswell and Boyle's equations [46].

Experimental BMP tests (BMP_{ex}) were conducted using an AMPTS II [Bioprocess Control] [47] using a 1:1 inoculum-to-substrate VS ratio. Reactors were flushed with nitrogen to ensure anaerobic conditions. After flushing, reactors were maintained at 45 °C, to simulate the incubation temperature of Scrivelsby Farm, for a duration of 15 days. Blank reactors were used to determine residual biomethane generation of only the inoculum. BMP tests were conducted in duplicate, unless stated otherwise.

Initially, BMP_{ex} of mono-digestions were performed; comparing a selected roadside verge grass (S2/H1.1) to maize. Sample S2/H1.1 was selected to perform batch digestions as this had the median BMP_{th} of the fresh verge grass samples. Mono-digestions were compared to co-digestions in Table 1; to understand the effect of the addition of verge grass into a typical agricultural feedstock co-digestion mix at Scrivelsby. A co-digestion containing 10% verge grass displaces the current grass

Table 1
Feedstock proportions of co-digestion mixtures. CD0 = Co-digestion containing 0% verge grass, the mix typically used at Scrivelsby Farm. CD10 = Co-digestion containing 10% verge grass. CD30 = Co-digestion containing 30% verge grass.

Sample	Feedstock Proportion (%)					
	S2/ H1.1	Maize	Straw	Farm Grass Silage[a]	Rye Grass	Chicken Litter
CD0	0	60	10	10	10	10
CD10	10	60	10	0	10	10
CD30	30	40	10	0	10	10

[a] Farm grass silage sample is not a verge grass sample, but grass silage generated on-site by Scrivelsby Farm.

silage used on-site by Scrivelsby Farm. The co-digestion containing 30% verge grass displaces the on-site grass silage and a proportion of the maize feedstock.

A 10 g sample of dried biomass was mixed with 100 mL of distilled water and incubated in a water bath at 50 °C for 48 h to emulate the low-temperature thermal hydrolysis pre-treatment at the Scrivelsby AD plant. All biomass samples were subject to low-temperature thermal hydrolysis before conducting BMP_{ex} experiments. After incubation, samples were diluted to 10 g VS_L^{-1} using distilled water and 200 mL added to each reactor, therefore adding 2 g VS of each feedstock to the each reactor. The inoculum was diluted to 10 g VS_L^{-1} and 200 mL with added to each reactor; leaving a 100 mL headspace.

In order to compare the BMP of fresh and ensiled verge grass, 2 g VS of each sample was added to 100 mL of distilled water and incubated in a 50 °C water bath for 48 h. Samples were subsequently decanted into AD reactors, washing with 100 mL of distilled water to ensure entire particle transfer and creating a sample concentration of 10 g VS_L^{-1}. The ensiled grass was not dried, in order to prevent the loss of volatile fermentative compounds. Therefore the ensiled grass was manually cut to an approximate particle size of 2–3 cm, due to the high moisture content. It is assumed particle size did not affect the BMP. This was repeated on grass samples collected from two sites: S2/H1.1 and S9/H1.2. Biodegradability was calculated according Equation (2).

$$Biodegradability\ (\%) = \frac{BMP_{ex}}{BMP_{th}} \times 100 \qquad (2)$$

2.5. Quantifying grass supply and demand from AD plants in Lincolnshire

The biomass potential [48,49] of verge grass in Lincolnshire was assessed from both a supply and demand perspective using a mixture of statistical data (road lengths and widths and AD plant locations) and experimental data for grass yields and methane yields.

LCC provided files of road data from their MapInfo GIS system. These held details of each section of road in Lincolnshire including: location, length, classification and environment (rural or urban). The operational farm-fed AD plants in Lincolnshire, their feedstock use and electricity generation capacity were identified from the Biogas Map [50], and the ADBA (Anaerobic Digestion and Bio-resources Association) map of AD plants [51].

The theoretical supply of biomass that could be harvested in Lincolnshire was estimated from road lengths and average verge width. It was assumed that all rural roads have grass verges and this assumption could mean that the grass potential is over stated. This area was then reduced as constraints were applied for practicality and economic factors. The ARCMap geographical information system (GIS) was used to calculate the length of rural road-verge within 3 km, 5 km, 10 km, 15 km, 20 km, 25 km and 30 km of any of the AD plants. The annual theoretical biomass potential (the total biomass produced) and the realistic biomass potential (the amount that can realistically be harvested subject to technical constraints of topography and technology, and economic and social constraints) [52] were then calculated from the constrained harvest areas, the average verge width, grass yield from 2016 tests, and assuming a single cut each year. The primary and secondary energy potentials [53] were then calculated assuming AD with CHP using LHV of grass of 21 MJ kg^{-1} [54], and methane potential of the test samples. OFGEM standard energy consumptions [55] were used to calculate the number of homes that could be heated and the number that could be powered by the heat and electricity produced from CHP.

The demand for verge grass was assessed from the total feedstock demand of the AD plants and assumptions of percentage of feedstock that could be replaced by grass.

2.6. Calculating harvesting costs

Harvesting was expected to be the main cost in the processing of grass in AD and the main input of energy into the system. Detailed cost models were built (in MS Excel) for the use of one or two harvesting vehicles. The single vehicle model estimated the cost of harvesting a tonne of grass by considering a leased harvester travelling from an AD plant to a harvest site (an average distance of 0.7 x harvest area radius) at driving speed, harvesting at cutting speed until full capacity was reached, then driving back to the farm at driving speed and finally unloading. The model used tractor driving and cutting speeds, tractor capacity for holding grass, an assumed grass yield, maximum working day length, cost per day of leasing, manning and fuelling a tractor and bespoke harvesting machinery (from the 2016 and 2018 harvests, see table 8 in supplementary data), swath width and harvest area radius. The two vehicle model considered a harvester driving to site and harvesting, then a second tractor collecting the full trailer and replacing it with an empty trailer ready for the harvester to continue cutting while the second tractor delivered the full trailer to the AD plant and unloaded. It was assumed that the second tractor and driver could be deployed on other work between trips.

Comparing harvesting costs with the price of locally available AD feedstocks is a simple but effective way of assessing the profitability of grass harvesting. The economics of each AD plant will be different depending on: the size, age and efficiency of the plant, the costs of feedstocks and the use of the energy produced. The incentives payable for electricity or heat generated depend on the size and commissioning date of the plant. An economic model was produced for the three farms involved in the grass pilot, but it was concluded that the simple comparison of harvesting cost with market prices for comparable feedstocks was a more useful economic test when considering a number of different AD plants with different running costs, incentives and technical performances. At the three pilot farms all feedstocks are processed in the same way, with no specific pre-treatments required for any of them.

The AD feedstock prices in Table 2 were provided by a Lincolnshire farmer for comparison with grass costs calculated from the harvesting model.

2.7. Interviewing AD plant operators

Semi-structured interviews were carried out with five owners or operators of farm based AD plants. These interviews allowed the in-depth discussion of topics and the flexibility to pursue new topics as

Table 2
Examples of 2016 AD feedstock prices.

Feedstock	Cost per tonne
Maize 32% dry matter	£32
Grass	£0.9 per % dry matter
Chicken litter	£15
Sugar beet pulp	£24
Vegetable waste	£10
Wet straw[a]	Free/low cost

[a] Wet straw rejected by biomass power station in Lincolnshire.

they arose, while retaining enough structure to allow the data gathered from the interviews to be analysed consistently [56,57].

Topics covered in the interview included: the background of the interviewee, the age and capacity of their AD plant, current type and volume of feedstocks, diversification and renewable energy schemes undertaken and their attitudes to using and paying for verge grass. One face-to-face and four telephone interviews were held. Audio recording of each interview were made and transcribed before the data was analysed using NVivo (qualitative data analysis software). Interview candidates were recruited by advertising on the ADBA website, and at an ADBA research conference.

3. Results and discussion

3.1. Grass yield

In 2016 the test harvest collected 5.9 t of grass from a single cut 4.3 km run with a 1.1 m swath giving an average fresh yield of 12.5 t ha^{-1}. The grass was found to have an average moisture content of around 76% giving a dry matter content of 3.0 t DM ha^{-1}. The grass yield in 2016 was thought to be higher than average because of warmer and wetter than average weather in the East of England [58] providing good growing conditions for grass. The pilot in 2018 collected on average 3 tonnes per hour from a 1.2 m swath travelling at 5 km h^{-1} giving an average as received yield of 5 t ha^{-1}2018 was another unusual growing season: a very cold spell from late February to mid-April ('The Beast from the East') [59,60] was followed by an exceptionally hot and dry summer [61]. This resulted in late growth of grass with a moisture content of around only 25%. Although the as received yield was lower than in 2016 the dry matter content was higher at 3.75 t DM ha^{-1}.

3.2. Digestion results

The composition of the verge grasses and feedstocks is displayed in Table 3. The ash content of the verge grasses was significantly higher than the farm feedstocks; with an average of 17.9% and 19.1% for fresh and ensiled verge grass respectively. Nitsche et al., (2017) [45] found sports field grass contained 15% ash and Piepenschneider*et al.*, (2016) [28] an ash content of around 7%. The portion of ash is likely higher due to the harvesting equipment; collecting the grass through suction which may disturb and collect the top layer of soil. However, suction collection devices have significant advantages in the economic feasibility of the harvesting process [62]. The grass harvested in 2018 appeared to contain very little soil as this was removed from the grass in the suction hose.

The average BMP_{th} of fresh verge grasses was found to be 522 ± 10 mL CH_4 g_{VS}^{-1} and 493 ± 11 mL CH_4 g_{VS}^{-1} and ensiled verge grasses is 519 ± 14 mL mL CH_4 g_{VS}^{-1} and 490 ± 15 mL CH_4 g_{VS}^{-1} using Buswell's and Boyle's equations respectively. The standard deviation was relatively low, suggesting that the theoretical methane yields are similar across sampling sites. Fresh verge grass samples have similar BMP_{th} to ensiled samples, suggesting ensiling does not affect methane generation yields. Verge grass samples also have a similar or higher BMP_{th} than the farm feedstocks, except rye grass. Meyer et al., (2014) [27] found an almost identical BMP_{th} of roadside verge grass in Denmark, using the Boyle's equation; 490 mL CH_4 g_{VS}^{-1}. However BMP_{th} using elemental compositional analysis often provides an overestimation of methane yields by assuming complete biodegradation during AD, with no differentiation between the biodegradable and non-degradable fractions of the grasses [63]. Therefore, to obtain more representative methane yields, Fig. 3, displays the BMP determined experimentally (BMP_{ex}) for one sample of verge grass (S2/H1.1), maize and co-digestions listed in Table 1.

Mono-digested verge grass had a greater BMP_{ex} (222 mL CH_4 g_{VS}^{-1}) than maize (202 mL CH_4 g_{VS}^{-1}). Though there is not a significant difference in methane yields, this does suggest that verge grass produces comparable levels of methane compared to farm feedstocks. S2/H1.1 has a biodegradability of 45% based on Boyle's equation (using the data in the supplementary information). The Boyle's equation predicted BMP closest to the BMP_{ex} values, due to the consideration of protein and ammonia fractions [63]. In this study maize had a biodegradability of 43%, suggesting similar digestion characteristics to S2/H1.1. However, Whittaker et al., (2016) [47] found the BMPex of ensiled maize to be 51% higher than ensiled *M. giganteus*. Additionally Sawatdeenarunat et al., (2015) [64] report a BMP range between 286 and 324 mL CH_4 g_{VS}^{-1} for grass and 291–338 mL CH_4 g_{VS}^{-1} for maize. S2/H1.1 and maize fall below this range, suggesting the AD process is not optimised. However, comparatively S2/H1.1 generates competitive levels of methane

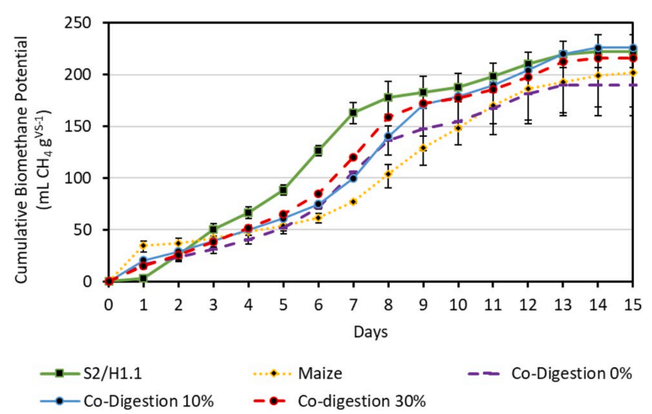

Fig. 3. Biomethane potential (BMPex) of the mono-digestions and co-digestion mixes. Standard deviations given as error bars.

Table 3
Compositional analysis of fresh and ensiled verge grasses compared to farm feedstocks.

Biomass Category	Biomass Type	Proximate Analysis (db) (%)[1]			Ultimate Analysis (db) (%)[1]					C:N	BMP_{th} Buswell (mL CH_4 g_{VS}^{-1})	BMP_{th} Boyle's (mL CH_4 g_{VS}^{-1})
		Volatile Matter	Fixed Carbon	Ash	C	H	N	S	O			
Verge Grass	Fresh	67.0 ± 2.3	15.2 ± 0.8	17.9 ± 2.0	41.1 ± 1.1	5.4 ± 0.3	2.1 ± 0.3	0.2 ± 0.1	33.4 ± 1.0	20	522 ± 10	493 ± 11
Verge Grass	Ensiled	68.9 ± 4.9	14.9 ± 1.6	19.1 ± 5.4	41.1 ± 2.4	5.3 ± 0.3	1.9 ± 0.2	ND	33.7 ± 2.9	23	519 ± 14	490 ± 15
Farm Feedstocks	Straw	77.5	12.4	10.1	44.5	6.0	0.6	ND	38.8	74	500	466
	Grass Silage	74.7	18.1	7.2	44.1	6.2	1.2	ND	41.4	37	480	492
	Rye Grass	73.9	18.4	7.5	47.0	6.4	1.8	ND	37.2	26	538	515
	Maize	80.1	16.6	3.4	45.2	6.7	1.3	ND	43.3	35	482	467

ND = not detected. db = dry basis. Average compositional analysis values given for the fresh and ensiled verge grass. Standard deviations of BMP_{th} given across the 9 fresh grass and 7 ensiled grass sampling sites. [1]Proximate and ultimate data for individual sampling sites is referenced in Table 7.

compared to maize. Agricultural AD operators often consider the biomethane yields on a dry matter (DM) basis, rather than VS. The moisture content of S2/H1.1 was 87% and maize; 74%. Accounting for this gives the biomethane potential on a dry matter basis; S2/H1.1 (191 mL CH_4 g_{DM}^{-1}) and maize (195 mL CH_4 g_{VS}^{-1}). Therefore there is little difference between biomethane potential on a DM basis between verge grass and maize.

During digestion an optimal carbon-to-nitrogen (C:N) ratio of 25:1 is recommended [65] to maintain efficient microbial metabolism without nitrogen deficiency or ammonia inhibition. The average C:N are 20 and 24 for fresh and ensiled verge grasses respectively, shown in Table 3. Verge grasses have more optimal C:N than all farm feedstocks, except rye grass.

During this case study it is assumed that the verge grass would contribute towards a co-digestion mix; rather than be digested as the sole feedstock. Co-digestions have the potential to overcome the issues associated with grass mono-digestion; imbalanced C:N, lack of trace minerals and high total solids. Previous studies have conclude grass collected from public spaces should be co-digested to maximise process efficiency [45,66].

Fig. 3 displays the BMP_{ex} of co-digestions described in Table 1. CD0 generated significantly less methane than S2/H1.1 and maize mono-digestions, despite the suggested benefits of co-digestions. However, both CD10 and CD30 generated higher methane yields than CD0 and maize mono-digestion. CD10 generated the highest methane yields of 226 mL CH_4 g_{VS}^{-1}. Therefore, verge grass substitution into a co-digestion appears to enhance biomethane generation, compared to the standard co-digestion mix.

3.3. Ensiling

Maintaining the balance between supply and demand of feedstock is crucial to ensure successful operation of an AD plant. Ensiling is a feedstock preservation method, currently used by AD operators to manage year-round use of perishable biomass. However, it is important prolonged storage does not impact biomethane yields. Table 4 displays the biomethane yields for fresh and ensiled verge grass across two sites: S2/H1.1 and S9/H1.2. There appears to be no significant difference in biomethane potential of fresh and ensiled grass for both sites analysed, however, numerically, ensiled verge grass samples generate higher methane yields. Piepenschneider et al., (2016) [28] found the biomethane potential of roadside verge grass silage to be 221–241 mL CH_4 g_{VS}^{-1}, lower than the values found in this study. This could be due to the separation of the grass silage into a press cake and organic-rich fluid by Piepenschneider et al., (2016); a stage not considered in this study. During ensiling it is important to minimise dry matter (DM) losses, Whittaker et al., (2016) [47] found 4% DM losses of miscanthus ensiled for 3 months. Table 4 suggests the moisture losses between samples is highly variable. Site S2/H1.1 found fresh grass had a higher moisture content compared to ensiled grass and site S9/H1.2 the opposite. VS content of the ensiled grass does not deplete during the ensiling period, compared to the fresh grass samples. Accounting for the higher BMP_{ex} and higher VS content, it is suggested ensiled grass is suitable for preserving the feedstock and subsequent biomethane potential.

Table 4
Volatile solid content and biomethane potential of fresh and ensiled verge grass samples from sites S2/H1.1 and S9/H1.2.

Sample	Moisture losses* (%)	VS (%TS)	BMP_{ex} (mL CH_4 g_{VS}^{-1})
Fresh S2/H1.1	87	86.1 ± 0.1	260 ± 0.5
Ensiled S2/H1.1	75	95.3 ± 0.1	276 ± 1.2
Fresh S9/H1.2	75	80.3 ± 0.2	244 ± 4.2
Ensiled S9/H1.2	80	84.6 ± 0.3	249 ± 2.8

Volatiles solids (VS) reported as a percentage of total solids (TS). Biomethane potential reported after 15 days of digestion. *after drying in 60 °C drying oven. Standard deviation displayed.

3.4. Harvesting costs

The 2018 harvesting vehicle could travel at 60 km h^{-1} and harvest at 5 km h^{-1} in dry conditions but only 3 km h^{-1} in very wet conditions. It had a capacity of 15 t of cut grass and used a 1.2 m swath. Higher swath widths were possible but would reduce manoeuvrability.

Harvesting costs were modelled for one and two vehicles. The cost per tonne of using one or two vehicles was not significantly different, but using two vehicles does provide the option of harvesting more grass in a day. The harvesting costs with a single vehicle using either a 1.2 m or 2 m swath are shown in Fig. 4. The harvesting costs are very sensitive to yield and speed of harvesting which is in turn influenced by how wet the grass is. Fig. 4 shows the costs for the 2016 fresh yield of 12.5 t ha^{-1} and a harvest speed of 4 km $h^{-1)}$ (a higher yield and average harvest speed) and the costs for the 2018 harvest (with a lower fresh yield of 5 t ha $^{-1}$ and the higher harvesting speed of 5 km h^{-1} achievable in very dry conditions).

In 2016 the grass had a dry matter content of 24% so would expect to achieve a price of £21.60 per tonne, based on the quoted cost of £0.9 per tonne per percent of dry matter. Harvest costs below this level can be achieved even with a 1.2 m cut up to a radius of around 40 km. The harvesting costs suggest that the grass harvested could be an economic feedstock. In 2018 the lower yield resulted in higher harvesting costs but the significantly higher dry matter content would result in a higher price being achieved. No other data on verge harvesting costs were available in literature for comparison, but previous research [30] has suggested that subsidies may be required for harvesting. Our results suggest that harvesting was economically viable in both 2016 and 2018 in Lincolnshire without subsidies, and costs will not place any constraints on the volume of biomass available for AD.

3.5. Quantification of verge grass potential

3.5.1. Supply

The total lengths of rural roads within potential harvesting areas were extracted from the LCC GIS road datasets and are included in Table 5. The total mass of verge available for cutting within these areas for the 2016 fresh grass yield (12.5 t ha^{-1}) and average 3 m verge width (at each side of the road) [4] are also shown in Table 5. For Lincolnshire as a whole this was 58 000 t. A 3 m harvest width is unlikely to be technically accessible so the realistic width of harvesting was limited to 2 m, reducing the potential to 38 000 t. In practice, when a 1.1 m or 1.2 m cutting head is used, multiple swaths are cut from a verge, as is often done at road junctions to improve visibility. A wider cutting head could be used but is not common. Only the roads within 20 km of an AD plant were considered to be of practical interest for harvesting, see Table 5, as this includes 78% of all rural roads which could supply 30 000 t from a 2 m wide swath.

There are no competing demands for verge grass to reduce the supply for energy, and it has been shown that the verge grass costs less than conventional feedstocks so there are no economic constraints on the biomass potential for the harvesting areas considered here.

The primary and secondary energy potentials were calculated using methane potential of 25 m^3 t^{-1} DM from 2016 tests and fresh grass yield of 12.5 t ha^{-1} with 76% moisture, and are shown in Table 6.

3.5.2. Demand for verge grass

There were 23 farm-fed AD plants operating in the LCC area with a total feedstock capacity of 476 000 t per annum. Feedstock capacity is generally quoted as received weight not dry matter (and an operator will have to adjust the feedstock to compensate for variations in moisture content). Assuming verge grass makes up a maximum of 25% of the total feedstock a maximum of 119 000 t of fresh grass per annum could be

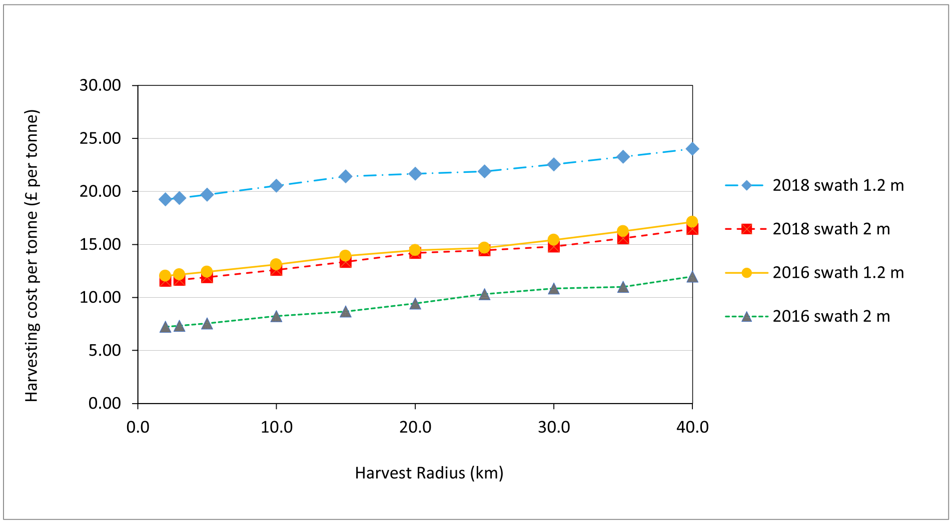

Fig. 4. Harvesting cost per tonne for 2016 test harvest and 2018 pilot.

Table 5
Length of rural roads within circular harvesting areas around 23 AD plants, and potential grass supply based on a single annual cut with yield of 12.5 t ha^{-1}.

Harvest Radius	Length of rural roads	% of total rural roads	Area of verge from 3 m cut	Mass of verge grass from 3 m cut	Area of verge from 2 m cut	Mass of verge grass from 2 m cut	Area of verge from 1.2 m cut	Mass of verge grass from 1.2 m cut
km	km	%	ha	t	ha	t	ha	t
5	786	10	472	5895	314	3936	189	2362
10	2626	34	1576	19 695	1050	13 152	630	7891
15	4398	57	2639	32 985	1759	22 026	1056	13 216
20	6008	78	3605	45 060	2403	30 089	1442	18 054
25	6894	90	4136	51 705	2758	34 526	1655	20 716
30	7214	94	4328	54 105	2886	36 129	1731	21 677
Unlimited	7678	100	4607	57 585	3071	38 453	1843	23 072

Table 6
Biomass potentials assuming a single cut yielding 12.5 t ha^{-1}.

	Primary Energy potential	Secondary energy potential (heat and power)	Homes powered	Homes heated
	TJ	GWh		
Theoretical energy potential – based on all rural roads harvested to a width of 3 m	242	2291	323	107
Technically accessible energy potential - all rural roads harvested to a width of 2 m	161	1527	216	72
Realistic energy potential – roads within 20 km of an AD plant harvested to a width of 2 m	126	1195	169	56

used in Lincolnshire. The realistic estimate of a 30 000 t supply could meet 6% of the total feedstock demand. This confirms that there is no constraint on supply by lack of potential demand.

The locations of the plants are shown together with the road network and harvest areas of radii 20 km around each plant in Fig. 5. This shows that the 23 plants are fairly evenly spread through the county. The 20 km harvest areas have considerable overlaps suggesting that it may not be necessary to harvest up to this distance in many parts of the county.

The three farms in the 2018 pilot had a combined feedstock demand of 34 000 t per annum. A single harvest of width 2 m and fresh yield of 12.5 t ha^{-1} from a radius of 20 km of any of the three farms would supply 6780 t or 20% of the total demand. Even a lower-yielding second harvest would exceed the demand from these three plants indicating that for typical (500 kW) farm-fed plants even a 15–20 km harvest area may be larger than required. This is a smaller area than considered in previous studies [17,27], possibly because of the particularly wide verges in Lincolnshire, the size of the AD plants and the assumption that verge grass would take up only a maximum of 25% of the AD plant feedstock. The balance of supply and demand for grass will vary throughout any region depending on the size of AD plants, the distance between them and the road network density.

3.6. *Market for verge grass*

All five of the AD operators interviewed said that they would consider using verge grass as a feedstock (usually as a replacement for maize or rye), assuming that the grass was free of chemical contamination. Some of the interviewees were concerned about visible litter such as cans and packaging in the grass and its effect on their digestate. This was more of a concern when the digestate was sold or returned to growers of feedstocks than when it was used on the operator's own farm. Visible litter was of more concern than chemical contaminations. An operator who processes food waste and grass cuttings was not concerned by the presence of litter as it could easily be removed from the digestate after pasteurisation.

None of the AD operators wanted to harvest the grass themselves because they would not have machinery or manpower available. They all wanted the grass to be delivered but had a range of requirements:

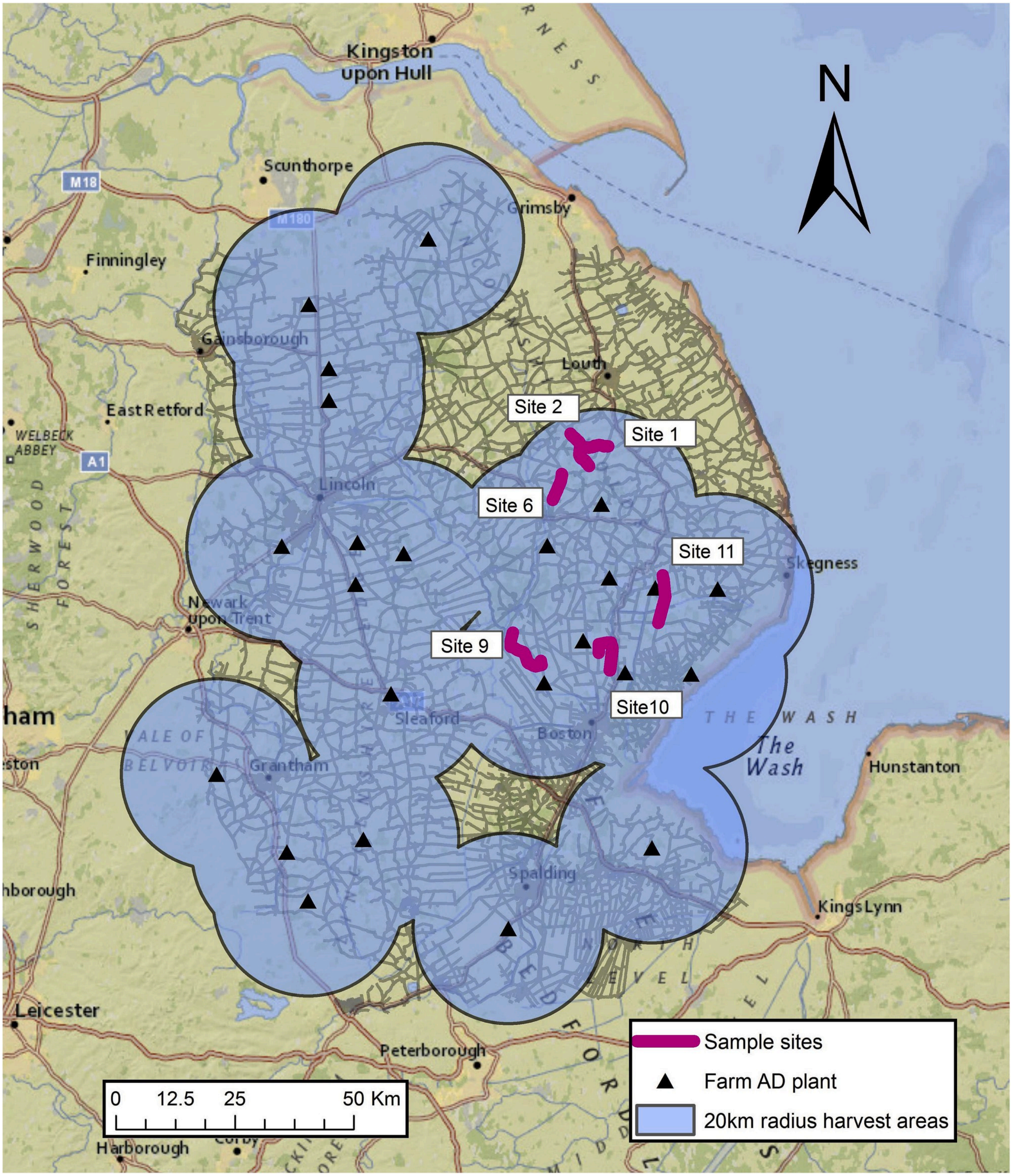

Fig. 5. Distribution of AD plants in Lincolnshire showing harvest radius of 20 km round AD plants, rural road network and grass sampling sites.

loose delivery was preferred by four interviewees but bailed or wrapped was also acceptable, and the smallest plant preferred boxed delivery. Three operators would require the harvested grass to be in short lengths (10 mm–25 mm). The larger operators required large deliveries (over 4000 tonnes) and doubted if grass could be supplied in large enough volumes for its use to be worthwhile. This is a valid concern and suggests that verge harvesting is more suitable for smaller plants (up to 500 kW with around 10 000 t feedstocks per annum) which would consider an annual grass consumption of up to 2500 t (based on 25% of total).

Four of the five operators said that they would use grass to make up a maximum of 25% of total feedstock in their digester. Four of the five AD operators were willing to pay between £10 and £20 per tonne for verge grass with a moisture content of 80%. This was above the cost of harvesting (under £9 per tonne harvesting with a 2 m swath within a 15 km radius of a plant) calculated for 2016. The operators who were willing to pay the highest price for the feedstock were those who had already used road or farm verge grass as a feedstock. This suggested that with use, confidence in the feedstock could grow.

Using an average price of £15 per tonne, a conservative estimate of the potential value of the most easily harvestable grass (available from a 1.2 m cut on verges within 20 km of an AD plant) in Lincolnshire is over £270 000 per annum.

Although only five interviews were held they covered a wide range of farm fed AD plant sizes and types, and the consistency of responses suggested that the findings were representative of UK AD operators.

3.7. Experience of the 2018 pilot

The pilot project experienced some initial teething problems with the new machinery but after resolution the harvester was found to perform well, meeting all the specifications for cutting and collecting grass. Soil sucked up with the grass was deposited in the suction hose and so soil contamination of the grass was avoided.

The unusually hot and dry weather resulted in very low grass yields from the first cut and in some of the pilot area a second cut was not carried out as there was insufficient growth. The farmers limited harvesting to areas within approximately 7.5 km of their plants as this was found to be a large enough area to provide them with the grass they wanted. Rather than expanding the area, a second swath width was taken from verges already cut, thus accessing the part of the verge with a higher grass yield. The farmers were initially keen to be in control of harvesting but may in future be happy to accept cut grass by contractors.

Experience of digesting the grass was good in both 2016 and 2018: no problems were encountered from soil contamination, no additional chopping or other pre-treatment was needed and no change in methane production was noted.

The main problem with the project was in obtaining permits from the Environment Agency for using verge grass in AD and spreading the digestate. Temporary approval had been gained in 2016, but once this expires in April 2019 the grass cannot be used. An application for a new waste code to be defined and included in EA AD regulations will have to be made to allow long term use of verge grass. Once approved this would allow all UK farm plants to digest verge grass. Despite the poor grass yield in 2018 the project team felt cautiously optimistic about continuing the project, subject to EA permitting, recognising that it may take 4–5 years to fully understand the impact and viability of verge harvesting.

4. Conclusions

Previous research has shown that road-verge grass has the potential to be used as a feedstock for AD to produce low carbon energy and to improve the biodiversity of the verges. Here we have extended the research to address some of the issues with implementing verge grass use: testing co-digestion of verge grass as a part of a typical farm-fed AD plant feedstock mix, testing the impact of ensiling, estimating the cost of harvesting grass and comparing this with the cost of other feedstocks and the price that farmers would be willing to pay for verge grass, and observing the digestion of verge grass at operational AD plants.

Road-verge grass has been shown in both lab-scale tests and in use in AD plants to be a technically suitable AD feedstock with digestion characteristics similar to those of other AD feedstocks. Both fresh and ensiled grass can be added to an AD plant feedstock mix, replacing energy crops such as maize or rye, resulting in reduced CO_2 emissions because of reduced fertiliser use. Enhanced verge biodiversity should also result. The use of a waste feedstock is especially attractive to UK operators wishing to source 50% of feedstocks from wastes to qualify for incentive payments.

In the Lincolnshire case study it was found that there was enough verge grass within transportation distances of 20 km of farm-fed AD plants to replace 6% of the county's AD feedstock demand. AD operators interviewed were willing to use up to 25% grass in their plants and pay more than the estimated harvesting cost, suggesting that harvesting may be financially viable without subsidies.

There is an opportunity for local authorities to reduce road maintenance costs by digesting harvested verge grass: either by outsourcing harvesting grass to groups of farmers or by selling grass harvested by road maintenance contractors. However, regulatory issues with waste permitting will need to be resolved before verge grass can be used at more than pilot scale. Lincolnshire is well suited to using verge grass because of its extensive network of rural roads, wider than average verges, fertile soils, and the relatively high concentration (for the UK) of operational farm-fed AD plants.

Other regions worldwide with temperate climates and widespread adoption of AD could also have the potential to digest grass from rural road and motorway verges, river banks and other public open spaces, particularly where these areas are regularly maintained for safety or aesthetic reasons. Feasibility will depend on the local supply of these types of biomass, harvesting costs and waste regulations, but in many areas economic harvesting of grass of a quality suitable for digestion could be achievable using harvesters similar to the one used in Lincolnshire. Given the figures presented in section 1.2 on the levels of AD in different countries, it would seem likely that the use of grass verge harvesting would be feasible in Europe and perhaps Asia and the USA as well. The novel methodology presented here for estimating harvesting costs and assessing biomass potentials has relevance beyond the UK and could be applied in other regions where the necessary road and AD plant data are available.

Verge grass is a resource from which local authorities could generate income, however the commercial viability of verge harvesting will not be fully understood until more experience is gained of the yields and compositions of verge grass and how they are influenced by weather, harvest schedules and local conditions. The long term impacts of collecting grass cuttings on the yield, composition and methane potential of verge grass also requires further research.

This work provides evidence that use of grass verge harvesting can support energy and carbon emissions reduction targets in suitable regions, and could be explored by local authorities interested in promoting biodiversity and looking for revenue generating schemes.

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Abbreviations

AD	Anaerobic digestion
ADBA	Anaerobic Digestion Bioresources Association
BMP	Biomethane potential
CHP	Combined heat and power
CNG	Compressed natural gas
DM	Dry matter
FIT	Feed-in tariff
LCC	Lincolnshire County Council
RO	Renewables obligation
RTFC	Renewable transport fuel certificate
PTE	Potentially toxic element
RHI	Renewable heat incentive
VS	Volatile solids

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2020.105570.

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