Renewable and Sustainable Energy Reviews 158 (2022) 112154

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Life cycle assessment of a short-rotation coppice willow riparian buffer strip for farm nutrient mitigation and renewable energy production

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ARTICLE INFO

Keywords:
SRC willow
LCA
Sustainability
Bioenergy buffers
Systems
Bioresources

ABSTRACT

As agricultural activity intensifies across Europe there is growing concern over water quality. Agricultural run-off is a leading cause of freshwater degradation. Simultaneously there is a continually increasing drive to promote renewable energy and reduce greenhouse gas emissions. Willow coppice planted as a riparian buffer has been suggested as a solution to help mitigate these problems. However, there is limited research into the use of such a system and several key knowledge gaps remain, such as, the energy ratio of the system is not known, and a fully harvested site has yet to be analysed in the literature. The aim of this research is to fill these knowledge gaps to help inform agri-environmental policy. To do this a life cycle assessment was carried out on an established willow buffer system, considering the global warming potential, eutrophication potential, acidification potential and cumulative energy demand impact categories, alongside the calculation of the energy ratio. To our knowledge it is the first site to be fully harvested and for which a full life cycle assessment has been carried out. The willow was combusted to fuel a district heating system. Key results showed emissions of 4.66 kg CO_2eq $GJ_{heatout}^{-1}$ and 0.01 kg SO_2eq $GJ_{heatout}^{-1}$, both of which are significant reductions compared to an oil heating system (95% reductions for both impact categories). The system also resulted in the permanent nutrient removal of 55.36 kg PO_4^{3-}eq ha^{-1} yr^{-1} and had an energy ratio of 17.4, which could rise to 64 depending on the harvest method.

1. Introduction

To meet increasing global demand, the agricultural sector has seen continual growth across the European Union (EU) over the past three decades [1]. However, as agricultural activities have intensified there has been growing concern over water quality. As of 2018, on average only 40% of surface water bodies across the EU were achieving 'Good or Better' ecological status, as defined by the Water Framework Directive (WFD) [2]. To put this into context, the aim of the WFD is for all surface water bodies to have 'Good or Better' ecological status by 2027 at the latest [3]. Agricultural activities are one of the main contributors to the degradation of surface water bodies due to nutrient run-off, which often results from the excess use of fertiliser (synthetic or organic) [2]. These nutrients can damage aquatic ecosystems through the process of eutrophication, which can cause widespread disruption to the entire ecosystem and leading to oxygen deficient 'dead zones' [4].

To mitigate this, riparian buffer strips have become more widely adopted across the EU [5]. A riparian buffer strip is an area within a defined distance of a local water body in which agricultural activities are restricted to protect water quality [9]. However, these buffer strips tend to be unmanaged and uncultivated [6], unpopular with farmers who see

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https://doi.org/10.1016/j.rser.2022.112154
Received 14 May 2021; Received in revised form 29 November 2021; Accepted 13 January 2022
Available online 2 February 2022

Nomenclature

Abbreviations

AFBI	Agri-Food and Biosciences Institute
AP	acidification potential
CED	cumulative energy demand
CH_4	methane
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
DH	district heating
DM	dry matter
EP	eutrophication potential
ER	energy ratio
EU	European Union
GHG	greenhouse gas
GIS	geographic information systems
GJ	gigajoule
GWP	global warming potential
ha	hectare
kg	kilograms
km	kilometre
LiDAR	light detection and ranging
l	litre
ILUC	indirect land use change
LCA	life cycle assessment
Mg	megagrams
P	phosphorus
$PO_4^{3-}eq$	phosphate equivalent
RED II	Revised Renewable Energy Directive
SO_2eq	sulphate equivalent
SOC	soil organic carbon
SRC	short rotation coppice
t	tonne
WFD	Water Framework Directive

them as unproductive [7], and to only temporarily decrease nutrient movements [8], leaking nutrients such as nitrates and phosphates once the strip has become saturated [7,8]. One measure that has been suggested is to strategically manage riparian buffer strips with fast growing woody tree species like short rotation coppice (SRC) willow to intercept overland water flow pathways and act as a bioremediation medium [9–11]. By regularly harvesting the willow, nutrients are permanently removed from the agricultural system, preventing saturation and ensuring the long-term effectiveness of the buffer strip for water protection services.

SRC willow, which has high growth and nutrient retention rates [12], is well suited to the temperate climate of northern Europe, where it is commonly used for bioenergy [13]. Unlike unmanaged riparian buffer strips, SRC willow can increase the productivity of land, by providing a revenue stream from renewable energy [9–11]. Through fossil fuel displacement, greenhouse gas (GHG) emissions can be reduced [14], while another suggested benefit is the 'mining' of nutrients from the agricultural system [9]. Phosphorus (P) absorbed during growth is expected to remain in the ash following combustion [15]. P is finite and costly and its recovery from ash could reduce demand for mineral fertiliser and contribute to the circular bio-economy [16]. Further advantages include increased soil carbon sequestration, biodiversity and flood alleviation [9]; as well as this, riparian buffer strips planted on land where agricultural activities are already restricted avoid competition with food production. Agriculture is key to meeting the United Nations Sustainable Development Goals [17], and so avoiding reduction in output and improving sustainability are of high importance.

While these benefits have been suggested in the literature, to date there has only been limited research into the use of dedicated SRC willow riparian buffer strips and the associated environmental impacts [11,18]. A thorough evaluation of the system is therefore required to investigate these impacts and to provide an evidence base for policy makers. While there has been considerable research into the environmental impacts of conventional SRC willow bioenergy plantations [14, 19–21] and those used to manage point source discharges of wastewater [12,22,23], the results cannot be directly applied to buffer strips as there are significant differences in the respective systems. There are, for example, no fertilisation or irrigation requirements for a riparian buffer strip system [24]. The willow grown on riparian buffer strips is also expected to benefit from increased light availability, as the buffer is likely to be relatively narrow (10 m) compared to typical plantations [24], and to have reduced pesticide usage, for water protection purposes [24].

Recent studies on established SRC willow riparian buffer strips have been published in both North America [8,24–26] and Europe [5], however, these papers did not consider the overall environmental impacts of the system, and focussed mainly on the impact on water quality and/or biomass yields. Furthermore, none of the buffer strips in these papers [5,8,24–26] underwent a full harvest. Previous work by these authors investigated the impacts on the food-energy-water nexus, but to our knowledge a life cycle assessment (LCA) has not yet been carried out on an established, fully harvested SRC willow riparian buffer strip system [18]. LCA is a technique commonly used to assess the environmental impacts associated with a product, process or service [27]. Furthermore, life cycle GHG emissions for biomass fuels must be reported to comply with the revised EU Renewable Energy Directive (RED II) [28]. LCA also allows environmental hotspots of a product or system to be pinpointed and has been described by the EU as a useful tool for informing policy [29]. One paper by Styles et al. [30] completed a life cycle assessment (LCA) for a hypothetical SRC willow riparian buffer strip. However, there were limitations to this work; the yield was taken from a large-scale unfertilised willow plantation and did not account for the benefits of increased light availability and the nutrients available in agricultural run-off; nutrient removal via harvest was not assessed and the energy ratio of the system was not calculated.

There are several key gaps in the research regarding SRC willow riparian buffer strips. To our knowledge an established SRC willow riparian buffer strip has yet to undergo a full mechanical harvest or been analysed for nutrient removal. Furthermore, the energy ratio for an SRC willow riparian buffer strip has yet to calculated for either a hypothetical or established plantation. The aim of this work was to assess the effectiveness of an SRC willow riparian buffer strip for both nutrient removal and energy production in order to inform agri-environmental policy. To do this an LCA was carried out to analyse an SRC willow riparian buffer strip which had been established on a working research farm, under temperate climatic conditions. Following a full harvest, nutrient removal and energy production capacity were assessed. Environmental hotspots of the system were also pinpointed, and alternative production pathways were assessed.

2. Materials and methods

The LCA was carried out according to the standard methodological framework: goal and scope definition, inventory analysis, impact assessment and interpretation of results [31]. The LCA software SimaPro v9 [32] was used as a basis for the LCA model and to complete impact assessment calculations.

2.1. Goal and scope

In order to evaluate the environmental and energy impacts of an established SRC willow riparian buffer strip a pilot site at the Agri-Food and Biosciences Institute (AFBI) in Hillsborough, Northern Ireland (54°27′15.3″N 6°04′59.0″W) was investigated (Fig. 1) as a case study. The 30 year mean annual temperature for the site is 8.8–9.2 °C [33], and the average annual rainfall is 896 mm [34]. The impacts of varying transportation distances, yields and harvesting technologies were analysed. The study considered the impact of the system from its cultivation to its termination along with the use of heat produced in a district heating (DH) system but did not consider the end use efficiency of the heating appliances used. It is therefore considered a cradle-to-plant analysis.

2.1.1. Functional unit (FU)

As an SRC willow riparian buffer system is for both environmental protection and energy production, two functional units were selected: '1 ha of SRC willow riparian buffer' and '1 GJ of heat produced'. Both functional units are regularly used in the literature for the assessment of SRC willow plantations [12,19,30,35–37].

2.1.2. System description and boundaries

SRC willow was planted at the site (formerly grassland) in May 2016 and was cut back after one year, to encourage the growth of multiple shoots, as is standard practice [38]. Due to ongoing parallel experiments at the site, many of the establishment processes typically carried out using conventional farm machinery, such as planting, site preparation and harvest, were instead carried out by hand. However, for the LCA inventory it was assumed that the processes took place in the conventional manner to give a better understanding of real-world application. No fertiliser was applied to the SRC willow riparian buffer strip. Herbicide was applied prior to planting only.

The first harvest was 2.8 years after cut-back. The harvested willow chips were transported 2 km by tractor and trailer to drying facilities before being combusted in an adjacent biomass boiler (85% efficiency) for district heating, displacing heat from an oil-fired system. Eight three-year harvest cycles were assumed before plantation termination, giving a total plantation lifetime of 25 years. The construction of infrastructure was not included in the system boundaries (Fig. 2), in line with RED II [28]. It was assumed that the ash produced by willow chip combustion would be applied in a fertiliser blend on the farm, but this activity was outside the system boundaries. As the willow was planted on unfertilised grassland it was assumed that there would be no long term change in soil organic carbon (SOC) levels [14,35].

2.2. Inventory analysis

2.2.1. Willow yield and nutrient removal

The willow was planted on three plots (P1, P3, P5, Fig. 3), alternated with unfertilised grassland (P2, P4, P6). The first willow harvest took place in February 2020. Harvest losses of 10% are usually associated with mechanical harvest [20] and so this factor was applied to the final yield value from hand harvesting (Table 1). The yield was calculated for 8 three-year harvest rotations and divided by the plantation lifetime (25 years). Multi-year studies have shown that although yield increases in the second and third cycle of willow harvest, it decreases again in the subsequent harvest cycles due to plant mortality [39]. Therefore, a constant yield was assumed for each harvest, based on the initial harvest yield.

The yield was markedly lower in plot 5 (P5) compared to P1 (Table 1). This was likely due to herbicide spray, from an adjacent field closest to P5 (Fig. 3), drifting over the willow plots during establishment; however, it is also possible that the lower yield resulted from lower nutrient or water availability or another difference in conditions. As both could occur in practice, the yield for P5 was included in the calculation of the mean (11.31 Mg dry matter (DM) ha^{-1} yr^{-1}) for the base case LCA. Three random samples of harvested willow from each plot (nine samples altogether) were selected and chipped into sealed plastic bags and cold stored. The samples were tested for moisture content, calorific value, and nutrient content (Table 1) according to Forbes et al. [40]. As the results of each analysis were evenly distributed the mean values from each were used as inputs for the LCA model (Fig. A1). The removal of nutrients was allocated to the harvest phase. The willow chips were expected to be burned at about 20% moisture content [38], therefore the calorific value was adjusted using the method from Hammar et al. [41] to give 17.4 MJ kg^{-1} DM at 20% moisture content.

2.2.2. Background processes

Data regarding all background processes involved in willow establishment and management were taken from the Ecoinvent database [42] and from literature sources (Table 2). It was assumed that 16,500 cuttings ha^{-1} would result in a plantation density of 15,000 plants ha^{-1}

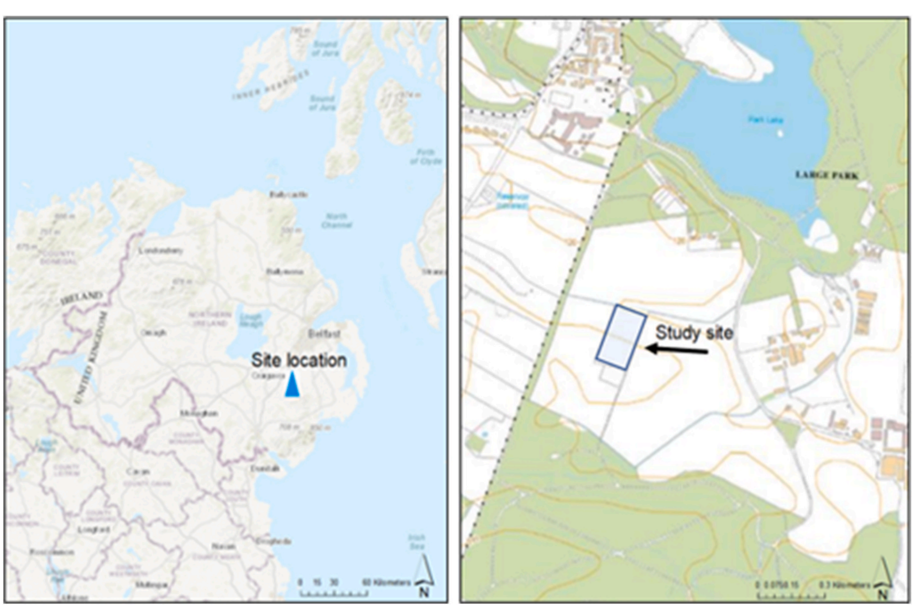

Fig. 1. Left figure: Map of Northern Ireland indicating the site location. Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community. Right figure: Ordnance survey map showing the study site. Based upon Land and Property Services data with the permission of the Controller of Her Majesty's Stationery Office, © Crown copyright and database rights MOU203.

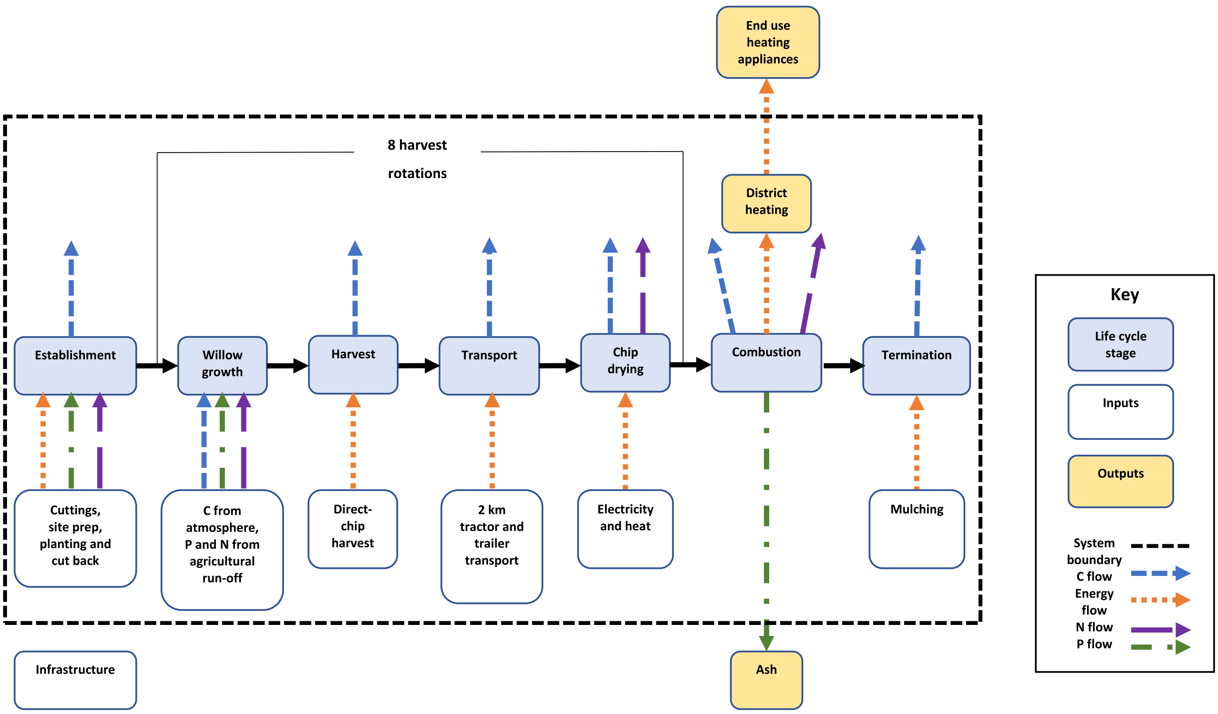

Fig. 2. System flow chart for base case scenario. C = carbon, P = phosphorus, N = nitrogen.

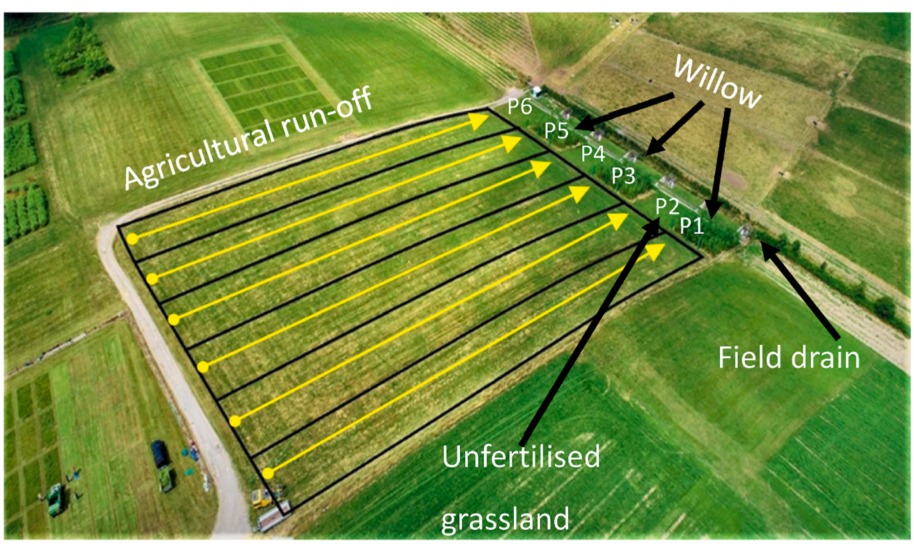

Fig. 3. Aerial view of willow plantation at AFBI. P= Plot; P1, P3 and P5 are under willow, P2, P4 and P6 are unfertilised grassland. AFBI = Agri-Food and Biosciences Institute (Do not scale).

Table 1
Willow harvest data and results from laboratory analysis.

Plot	Mass Mg	Area m^2	Moisture content %	Yield Mg DM ha^{-1} yr^{-1}	Yield Mg DM ha^{-1} yr^{-1} (10% harvest losses)	Calorific value MJ kg^{-1} DM	P g kg^{-1} DM	N g kg^{-1} DM
P1	1.106	123.19	52.82 (0.22)	14.52	13.07	19.5 (0.04)	0.91 (0.04)	5.0 (0)
P3	1.008	128.04	52.92 (0.31)	12.71	11.44	19.6 (0.08)	0.89 (0.05)	5.8 (0.62)
P5	0.808	125.13	52.59 (0.59)	10.5	9.45	19.6 (0.11)	0.88 (0.03)	5.1 (0.37)
Mean	0.974 (0.12)	125.45 (2.0)	52.78 (0.14)	12.57 (1.6)	11.31 (1.5)	19.6 (0.05)	0.9 (0.01)	5.3 (0.37)

DM = dry matter. Standard deviations in brackets.

Table 2
Life cycle inventory for 1 ha of SRC willow riparian buffer strip over its 25-year plantation lifetime.

Life cycle stage	Operation/ SimaPro input	Description	Iterations
Establishment	Cutting production	Includes all nursery activities involved in the production of 16,500 willow cuttings.	1
	Cutting transport[a]	Willow cuttings transported 165 km from a local nursey to the AFBI site.	1
	Herbicide spraying	Use of a small field spreader for pre-ploughing herbicide spraying.	1
	Glyphosate production	Production of 6 l of glyphosate for pre-ploughing herbicide spraying.	1
	Ploughing	Field ploughed to a 25 cm depth.	1
	Harrowing	Field harrowing by rotary harrow.	1
	Planting	Willow cuttings planted using a step planter.	1
	Rolling	Field rolled post planting.	1
	Cutback	Willow cutback after 1 year of growth using a rotary mower.	1
Harvest[b]	Direct chip harvester	Use of Ny Vraa side harvester, diesel consumption taken as 51 l ha^{-1} [43].	8
	Tractor and trailer	74.85 tkm of on-field fresh willow chip haulage.	8
Transport	Transport	Willow chips transported 149.7 tkm by tractor and trailer to drying sheds.	8
Drying[c]	Electricity	1931 kWh_e, taken from the Irish grid, to power fans which blow hot air through the willow stacks.	8
	Heat	6370 MJ_{heat} provided by previously dried willow chips at AFBI, burned at 20% moisture content, with an energy content of 17.4 MJ kg^{-1} DM [41]. CH_4 and N_2O emissions from the combustion of willow chips set to 11 g GJ_{fuel}^{-1} and 6 g GJ_{fuel}^{-1} respectively [41].	8
Termination	Mulching	Willow stools reincorporated into the soil using a rotary cultivator.	1

SRC = short rotation coppice, AFBI = Agri-Food and Biosciences Institute, DM = dry matter.
[a] Cuttings transported by a light commercial vehicle, assuming a load of 0.33 t [42]. All transportation inputs include an empty return journey of the same distance. Diesel fuel used for both transport and field activities. Both direct emissions from diesel consumption and indirect emissions from diesel consumed were accounted for.
[b] 74.85 Mg ha^{-1} of fresh chips (52.78% moisture) harvested each rotation.
[c] Drying requirements (heat and electricity) for willow chips at a moisture content of 52.78% to be dried to 20%, adapted from Wolsey et al. [22].

Fig. 4. Ny Vraa side harvester attached to tractor and trailer, in use at AFBI Large Park Hillsborough, Northern Ireland. Photo taken by Oliver Carville. SRC = short rotation coppice, AFBI = Agri-Food and Biosciences Institute.

according to the 'SRC Willow Best Practice Guidelines' for the island of Ireland [38]. The requirement for pre-ploughing herbicide application was also taken from this document. Harvesting was assumed to be with a Ny Vraa side harvester attached to a tractor and trailer (Fig. 4).

2.3. *Impact assessment*

An attributional LCA was carried out, with the impacts assessed using the CML 2015 method [44]. As the main functions of an SRC willow riparian buffer strip are to protect local water bodies and produce renewable energy, the impact categories assessed were acidification potential (AP), eutrophication potential (EP) and global warming potential (GWP_{100}). Alongside this, the cumulative energy demand (CED) was calculated, which allowed the energy ratio (ER) to be determined. The results were compared with a conventional SRC willow plantation grown in Ireland assessed by Murphy et al. [14]. The results were also compared with the environmental impacts of heating oil used for district heating purposes, which is the fossil fuel system being replaced.

AP refers to emission of acids or acid forming substances into the environment and is expressed in kg SO_2eq/FU [45]. EP is the potential of discharged nutrients to cause over-fertilisation of water and soil and is expressed in kg PO_4^{3-}eq/FU [45]. The main contributors to EP are phosphorus, nitrogen and their associated compounds [45]. GWP is the sum of the GHGs released during the life cycle of the system and is expressed in kg CO_2eq/FU [45]. CED accounts for both direct and indirect energy inputs and is given in J/FU. CED has been shown to correlate well with most environmental life cycle impact categories and is a good indicator of the overall environmental impacts of the system [14]. ER is the ratio between useful energy output from the biomass boiler and the direct and indirect energy input throughout the system lifecycle. A positive ER is particularly important in the evaluation of bioenergy systems as it signifies that more energy is produced than consumed.

2.4. *Sensitivity analysis*

Sensitivity analysis was undertaken for three main scenarios (Table 3): yield (A), transportation distances (B), and harvest technology (C). To our knowledge this is the only dedicated SRC willow riparian buffer site harvested to date and so there is still uncertainty regarding typical yields. Therefore, the impacts of lower (A1) and higher (A2)

Table 3
Scenario descriptions for sensitivity analysis.

Scenario	Yield Mg DM ha^{-1} yr^{-1}	Transportation distance[a] km	Mode of transport	Harvest technique
Base case	11.31	2	Tractor and trailer	Direct chip
Yields				
A1	9.45	2	Tractor and trailer	Direct chip
A2	13.07	2	Tractor and trailer	Direct chip
Transport distance				
B1	11.31	50	Tractor and trailer	Direct chip
B2	11.31	50	Truck	Direct chip
B3	11.31	100	Truck	Direct chip
B4	11.31	250	Truck	Direct chip
Harvest technology				
C1	11.31	2	Tractor and trailer	Whole stem
C2	11.31	2	Tractor and trailer	Biobaler
C3	11.31	250	Truck	Whole stem
C4	11.31	250	Truck	Biobaler

[a] This is the distance from the plantation to the drying facility. It is assumed that the biomass boiler is co-located with the drying facility. DM = dry matter.

yields from P5 (9.45 Mg DM ha^{-1} yr^{-1}) and P1 (13.07 Mg DM ha^{-1} yr^{-1}) respectively were assessed. The AFBI system requires minimal transportation of the willow chip due to the proximity of the willow site to the drying facilities and biomass boiler (2 km). However, it is unlikely that all farms would have their own drying facilities and/or boilers, and actual transport distances might be higher. Impacts were therefore assessed for 50 km tractor and trailer transport (B1), and truck transport of 50 km (B2), 100 km (B3) and 250 km (B4). The maximum viable transport distance before the net energy production fell below zero was also determined.

The alternative harvesting techniques of whole stem harvest (C1) and bio-baling (C2) were also assessed (Table 3). Both techniques would negate the need for artificial drying which can be an energy intensive process. Diesel consumption for the full stem harvester was taken as 48 l ha^{-1} [43] and diesel consumption for chipping was taken as 106.4 l ha^{-1} [46]. The harvested rods were assumed to be transported to a storage facility adjacent to the biomass boiler and allowed to dry naturally to 20% moisture content before being chipped prior to combustion. For the bio-baler, diesel consumption was taken as 140 l ha^{-1} [47]. The bales were assumed to be left in the field to dry naturally to 12% moisture levels [47] before being transported to the biomass boiler. Two further scenarios (C3 and C4) were also assessed in which the willow was transported 250 km after whole stem harvest and biobaler harvest respectively.

3. Results and discussion

The base case willow chip production system resulted in emissions of 19.5 Mg CO_2eq ha^{-1} and 41.3 kg SO_2eq ha^{-1} over a 25-year plantation lifetime (Table 4). The removal of nitrogen and phosphorus in the harvested biomass resulted in a negative EP of −1384 kg PO_4^{3-}eq ha^{-1} over the plantation lifetime. The CED was 240 GJ.

3.1. Energy demand, energy production and energy ratio

The main contributor to the energy demand was the drying process for the willow chips which accounted for 84% of the total CED (Fig. 5). As the willow was chipped directly, artificial drying was required to prevent natural degradation and dry matter losses of the willow chips [38,48]. Due to the proximity of the field to the drying facilities and biomass boiler (2 km) the transport of the willow chips made only a minor contribution to the CED. The energy demand of the harvest phase (9%) was more than double that of the establishment phase (4%) as a result of regular harvest cycles (8) throughout the plantation lifetime.

Gross energy production was 4918 GJ ha^{-1} pre conversion and 4180 GJ ha^{-1} post conversion over the plantation lifetime, with net energy production of 3940 GJ ha^{-1} post conversion. This sits near the top of the range for energy production expected from conventional SRC willow plantations in Ireland (Table 5). It also compares favourably with miscanthus plantations in Ireland and, further afield, poplar plantations in Italy, assuming a similar calorific value for willow, miscanthus and poplar at 20% MC [38] and based on the average yield for poplar clones [49].

The energy ratio was calculated by dividing the gross energy output by the CED, resulting in an ER of 17.4. This is marginally higher than the ratio of 16.75 found by Murphy et al. [14] for their base case scenario in which the willow in a conventional plantation was produced and harvested in a similar manner to this study but with the addition of synthetic fertilizer application for each growth phase. However, Murphy et al. [14] did not include willow chip drying in their system boundaries, assuming the willow chips were burnt fresh from harvest in a large co-fired power plant. With similar assumptions, the energy ratio in this study rises to 95.8 which is almost six times higher than that found by Murphy et al. [14] and also significantly higher than the range of 3–16 for cradle-to-plant assessments reported in a review by Djomo et al. [51]. However, the burning of high moisture content wood is not recommended, especially for small-scale boilers, due to impossible or inefficient combustion [52].

Unlike a conventional SRC willow plantation, no fertiliser is applied to an SRC willow riparian buffer strip. Murphy et al. [14] found the use and production of synthetic fertiliser to be a significant contributor to the overall energy demand. Fertiliser usage and production is often cited as an environmental hotspot in LCA studies of SRC willow plantations and so avoiding this while maintaining a high yield is a key strength of the buffer system [19,53]. Another difference between this study and that of Murphy et al. [14] was the energy requirement of the harvest phase; the smaller side harvester used in this study consumed just over half the diesel required by the self-propelled harvester (57 l ha^{-1}, including tractor and trailer consumption, compared to 100 l ha^{-1}) used by Murphy et al. [14]. Alongside this a much shorter transportation distance was required in this study (2 km compared to 50 km); the impact of transportation distance is explored in the sensitivity analysis.

3.2. Eutrophication potential

The SRC willow riparian buffer strip system resulted in a nutrient input of 26.6 kg PO_4^{3-} ha^{-1} over the plantation lifetime, but when the removal of nutrients via willow harvest is considered (−1410 kg PO_4^{3-} ha^{-1} removed via harvest over the plantation lifetime), the system results in a negative EP overall. This indicates that the use of SRC willow as a riparian buffer strip is an environmental benefit, rather than burden, in this impact category. The nutrient savings in this study (−55.36 kg PO_4^{3-} ha^{-1} yr^{-1}) are much greater than those predicted in previous research (−33 kg PO_4^{3-} ha^{-1} yr^{-1}) by Styles et al. [30]. Styles et al. [30] did not consider the permanent removal of nutrients via willow harvest but rather the nutrient retention capacity of the buffer strip, and the lower EP value may be due to conservative estimates for nutrient retention based on older willow cultivars.

For hotspot analysis nutrient removal via harvest was ignored, and the main EP contributors were the establishment phase (32%), chip drying (32%) and combustion of the willow chips (30%) (Fig. 5). The EP associated with the drying phase and combustion of willow chips was due to the release of N_2O when the willow chip is burnt. The EP resulting from the establishment phase arose from the use of fertiliser as part of the production of the willow propagation material for planting. Despite the inclusion of chip drying and combustion in the system boundaries, the nutrient input in this study (0.006 kg PO_4^{3-} $GJ_{heatout}^{-1}$) is still lower than the value of 0.0092 kg PO_4^{3-} $GJ_{heatout}^{-1}$ found by Murphy et al. [14]. Again this is primarily due to the absence of synthetic fertiliser usage which makes up 57% of the overall contribution to the EP found by Murphy et al. [14].

Table 4
LCA results for 1 ha of willow production and a 25-year plantation lifetime.

Impact category	Unit	Establishment	Harvest	Transport	Chip drying	Combustion emissions	Termination	Total
GWP	kg CO_2eq	721	377	427	8530	9330	82.4	19,467
AP	kg SO_2 eq	4.18	3	2.5	31.1	0	0.522	41.3
EP	kg PO_4^{3-} eq	8.55	−1410	0.737	8.6	7.97	0.147	−1384
CED	GJ	9.62	21.5	6.03	202	0	1.15	240

GWP = global warming potential, AP = acidification potential, EP = eutrophication potential, CED = cumulative energy demand.

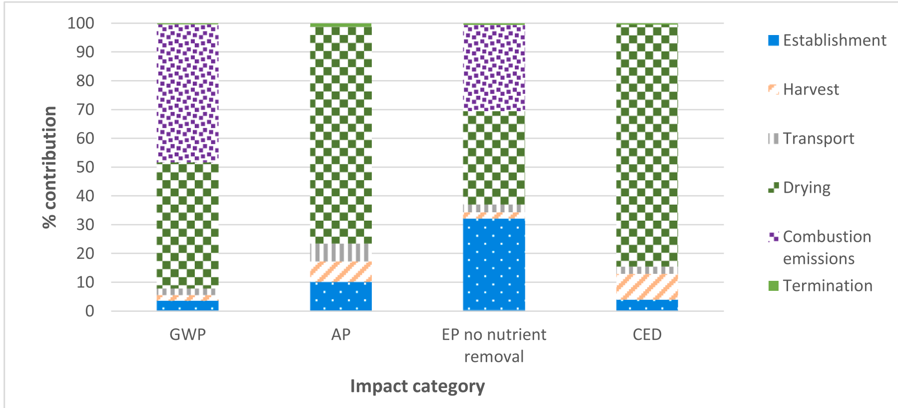

Fig. 5. Hotspot analysis for 1 ha of SRC willow riparian buffer. EP results do not account for the removal of nutrients via harvest.

Table 5
Comparison with other solid biomass crops.

Crop	Country	Yield Mg DM ha^{-1} yr^{-1}	Pre conversion gross energy production GJ ha^{-1} yr^{-1}	Reference
Willow riparian buffer	Ireland	11.31	197	Current research
Conventional willow	Ireland	7–12	122–209	[38]
Miscanthus	Ireland	8–10.4	139–181	[50]
Poplar	Italy	8.4	146	[49]

3.3. Acidification potential

Overall, the system had a minor acidifying effect on the environment, largely due to the use of grid electricity for drying (Fig. 5). The low impacts in this category (Table 4) are again due to the avoidance of either organic or synthetic fertiliser usage which have both been shown to be major contributors to the AP of SRC willow systems [14].

3.4. GWP

The largest contribution to GWP was from combustion (48%), due to the release of N_2O and CH_4 (which have CO_2 equivalency factors of 298 and 25 respectively [54]). It was assumed there was no net release of CO_2 due to the combustion of willow chips as is standard practice for bioenergy production systems. The chip drying process contributed 44%, mainly due to the use of grid electricity to power the fans. Overall emissions were 4.66 kg CO_2eq $GJ_{heatout}^{-1}$. This is similar to previously reported values for SRC willow plantations in which willow chips are combusted for district heating and changes in SOC levels are ignored [41,48,55,56]. It is lower than the 5.84 kg CO_2eq $GJ_{heatout}^{-1}$ reported by Murphy et al. [14] for similar climatic conditions (Ireland) despite the inclusion of combustion and willow chip drying in the system boundaries. The lower emissions were largely due to the avoidance of fertiliser which accounts for over 50% of the GWP in Murphy et al. [14]. Research from the USA, Sweden and Germany found similar results for conventional plantations with GWPs of 5.96 kg CO_2eq $GJ_{heatout}^{-1}$ [56], 3.65 kg CO_2eq $GJ_{heatout}^{-1}$ [55] and 11.2 kg CO_2eq $GJ_{heatout}^{-1}$ [21] respectively. Again, these papers did not include the emission of N_2O and CH_4 resulting from willow chip combustion in their system boundaries. If the impact of combustion emissions were ignored for the SRC willow riparian buffer strip system, the GWP would drop to 2.43 kg CO_2eq $GJ_{heatout}^{-1}$.

3.5. Sensitivity analysis

3.5.1. Transport

Of the impact categories considered, transportation distances had the greatest effect on the AP, with a three-fold increase for a distance of 250 km (scenario B4) compared to the base case (Fig. 6). This was due to acidifying emissions related to the combustion of diesel fuel. Transportation had a negligible impact on the EP of the system. Transport by tractor and trailer resulted in greater negative environmental impacts than transport by truck due to increased diesel usage, with truck transport over 100 km (scenario B3) resulting in less negative environmental impacts in all impact categories than transport by tractor and trailer over 50 km (scenario B1). This corresponds with previous findings in the literature [14].

In terms of GWP and ER the system performs well up to distances of 250 km. At 250 km the GWP rose to 8.1 kg CO_2eq $GJ_{heatout}^{-1}$ and the ER fell to 9 (Fig. 7), both of which lie in the expected range for conventional SRC willow plantations found in the literature [21,51,55]. The maximum distance for transport before net energy production fell below zero was 4042 km including an empty return journey. As the island of Ireland is only 167 km in width and 486 km in length [57], distances of this magnitude are much greater than those realised in the transportation network in Ireland. In a European context, this is roughly the equivalent of driving from Moscow to Madrid [58]. Therefore, in terms of environmental impacts and energy production, road transportation distance is not a limiting factor when implementing SRC willow riparian buffer strips.

3.5.2. Yield

One of the key strengths of the system was the high yield produced (from 9.45 Mg DM ha^{-1} yr^{-1} to 13.07 Mg DM ha^{-1} yr^{-1}) despite the absence of fertilizer usage (organic or synthetic). Yields of about 9.2 Mg DM ha^{-1} yr^{-1} could be expected from fertilised SRC willow plantations in Ireland [14]. Studies investigating the irrigation of SRC willow in Ireland with farmyard washings [23] and wastewater from a food processing plant [22], found yields of 10.94 Mg DM ha^{-1} yr^{-1} and 9.22 Mg DM ha^{-1} yr^{-1} respectively. Elsewhere yields of about 10 Mg DM ha^{-1} yr^{-1} are expected for fertilised plantations in Sweden [59], while in North America yields range from about 7 Mg DM ha^{-1} yr^{-1} [47] to 14.1 Mg DM ha^{-1} yr^{-1} [56]. Even the lowest yield (9.45 Mg DM ha^{-1} yr^{-1}) in our study was significantly higher than that in Styles et al. [30] (5.1 Mg DM ha^{-1} yr^{-1}). We suggest that the high yields found in our study result from a combination of increased light availability, as the strip is only 10 m wide, the availability of key nutrients in the agricultural run-off and the use of modern, high yielding varieties of willow clones.

The high yield scenario (A2) resulted in an increase in GWP, AP and CED on a per hectare basis compared to the low yield scenario (A1), suggesting that increased yield has a detrimental impact on the

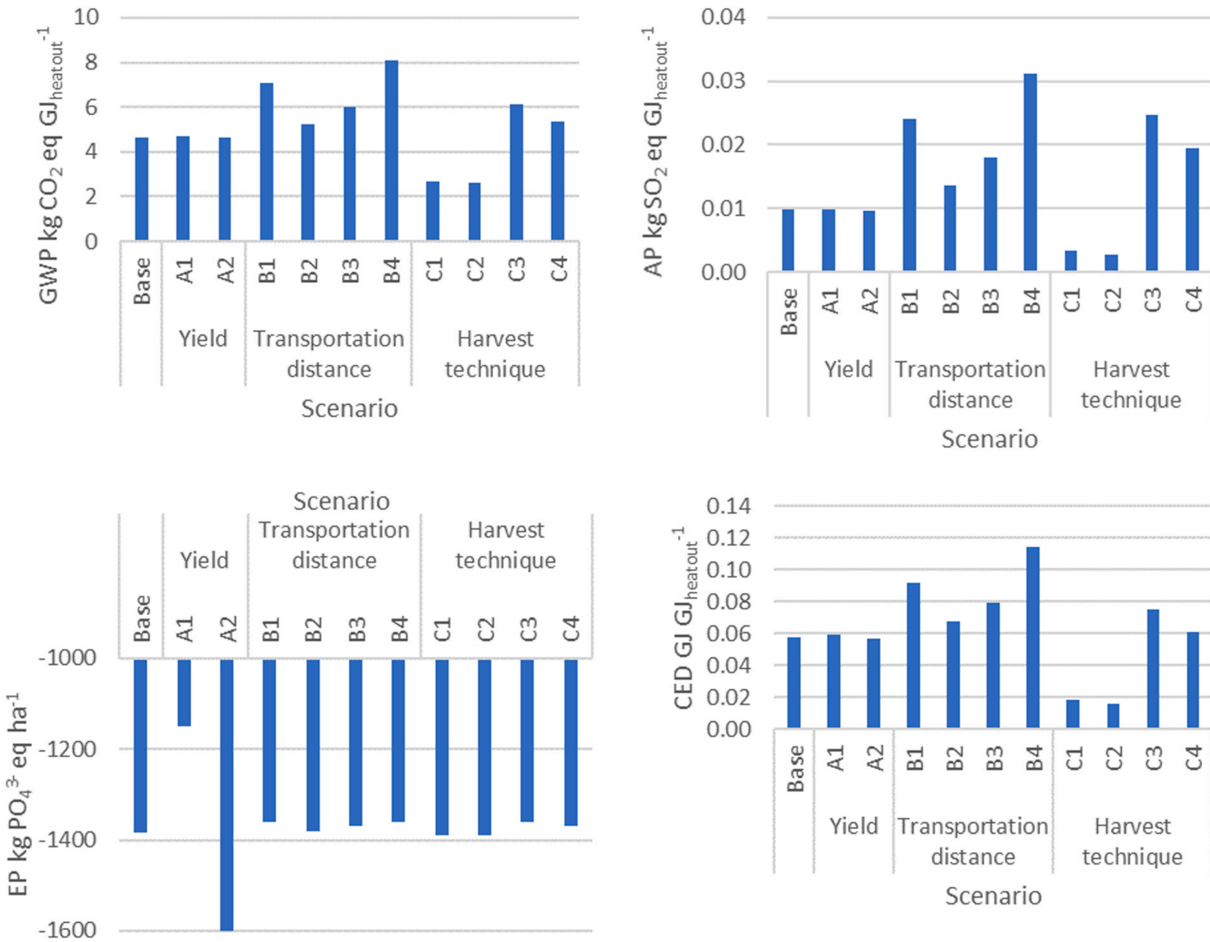

Fig. 6. Sensitivity analysis for each impact category. Refer to Table 3 for scenario descriptions.

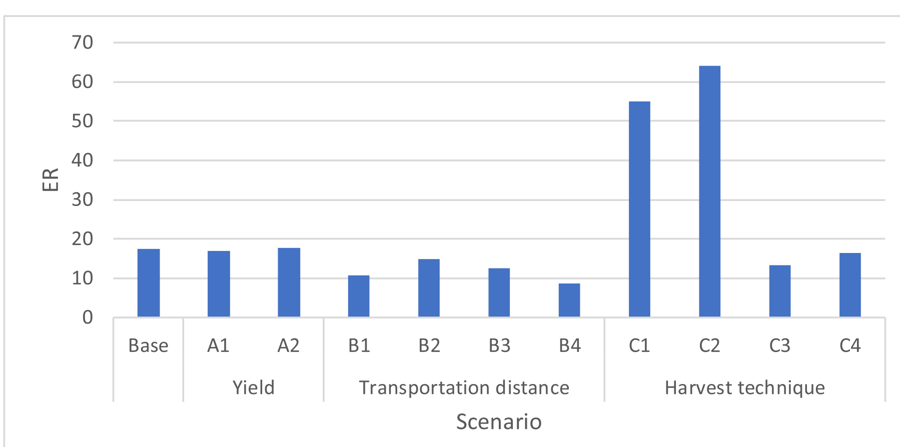

Fig. 7. Energy ratios for each scenario in the sensitivity analysis. Refer to Table 3 for scenario descriptions.

environment. This is due to increased drying requirements and transportation loads. However, if the functional unit considered is one GJ of heat produced, the results show that increased yield has a beneficial impact on the environment, as the higher energy production more than compensates for the negative impact of increased drying and transportation loads. This indicates the importance of selecting the most appropriate functional unit for analysis.

As the system is designed as a landscape intervention for water quality protection, the functional unit of 1 ha was selected when comparing the EP (Fig. 6), while the functional unit of one GJ of heat produced was applied to the GWP, AP and CED impact categories. The functional unit has no impact on the ER. In the high yield scenario, more nutrients were removed from the system in the harvested biomass, resulting in even further reductions in EP compared to the base case, highlighting the benefit of a strong yield. However, differences in yield had only a minor impact on the ER which ranged from 17 (scenario A1) to 17.6 (scenario A2), indicating a strong overall performance for the system even with relatively lower yields.

3.5.3. Harvest method

Both full stem harvesting (scenario C1) and harvesting with a biobaler (scenario C2) performed favourably compared to direct chip harvesting. The EP remained largely unchanged regardless of harvest method, as the amount of harvested willow, and therefore nutrients removed, remained the same. In all other impact categories, there were significant reductions in environmental impacts (Fig. 6). The ER was also substantially higher than the base case, at 55 for full stem harvesting (scenario C1) and 64 for the biobaler (scenario C2). The main benefit of both full stem and biobaler harvesting was that artificial drying, a major hotspot in the base case scenario, was not required.

The biobaler outperformed full stem harvesting in all impact categories, except the EP where they were the same. One of the reasons for this was the lower transportation loads for the biobaler system, as the bales can be left in the field to dry to about 12% moisture content [47] before being transported to the combustion boiler. In contrast, full stems are typically transported fresh from harvest, at about 53% moisture content (Table 1), and so are heavier, resulting in greater transportation loads. Loose full stems (which can be 6–8 m long) are also unwieldy and difficult to handle both at the harvest stage and when they are chipped prior to use. Another advantage of the biobaler was that by drying to just 12% moisture content [47], compared to around 20% for full stems, the lower heating value of the wood was increased, improving the overall energy performance. It must be noted that the 12% moisture content levels were taken from field trails in southern Canada [47], unpublished work by AFBI found moisture levels of 17% for bales left in Irish conditions which would slightly increase transportation loads and the environmental impacts of the biobale system in an Irish context.

Table 6
Comparison of oil-fired heating to heat from willow chips per $GJ_{heatout}$.

Impact category	Unit	Base case	Scenario B4	Scenario C2	Oil heating
GWP	kg CO_2 eq	4.66	8.1	2.6	88.7
AP	kg SO_2 eq	0.01	0.031	0.0027	0.183
EP	kg PO_4^{3-} eq	−0.33	−0.33	−0.33	0.0168
CED	GJ	0.057	0.11	0.016	1.3
ER	N/A	17.4	8.7	64	0.77

C2 = biobaler. B4 = 250 km transport.

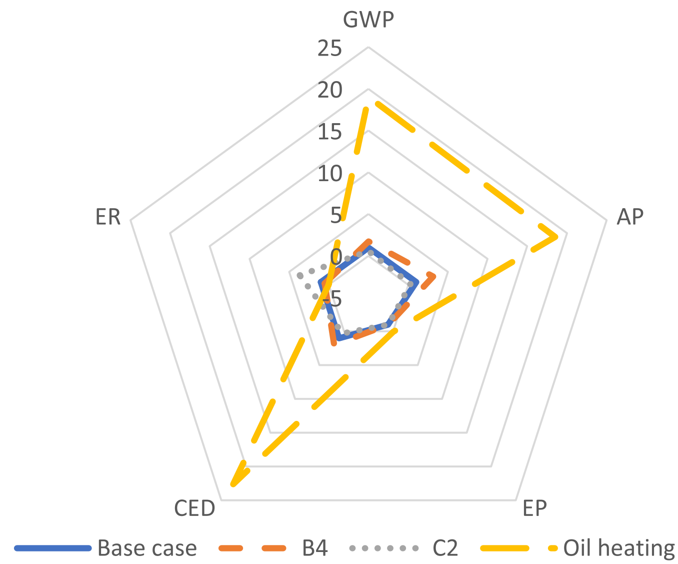

Fig. 8. Comparison of impacts for 1 $GJ_{heatout}$, as a proportion change from the base case, for the oil heating scenario and alternative willow chip production scenarios B4 (250 km transport) and C2 (biobaler). GWP = global warming potential, AP = acidification potential, EP = eutrophication potential, CED = cumulative energy demand, ER = energy ratio.

3.6. Comparison with fossil fuel

The environmental impacts of oil heating were modelled using the Ecoinvent database on SimaPro 9 for 1 $GJ_{heatout}$ using a 100 kW boiler. The production of light fuel oil and its combustion were included in the system boundaries. Compared to the oil-fired heating system, the willow system performed favourably (Table 6). The base case scenario had 95% less CO_2eq emissions (84 kg $CO_2eq/GJ_{heatout}$). Even with 250 km transport (scenario B4), CO_2eq emissions were reduced by 91%. Over the plantation lifetime, the use of willow chips for heat reduced emissions by 351 Mg CO_2eq ha^{-1} for the base case, rising to 366 Mg CO_2eq ha^{-1} for a biobaler system (scenario C2). Acidifying emissions were also reduced. The energy ratio was higher for the willow system in all scenarios and in particular with biobaler harvesting (Fig. 8). While the EP for the oil-fired system was relatively low, no ecosystem services are provided and there is no contribution to the circular bioeconomy, further highlighting the comparative strength of the SRC willow riparian buffer strip system.

3.7. Policy implications

RED II stipulates that from January 2021 electricity, heat or cooling produced from biomass sources in the EU must result in at least a 70% reduction in GHG emissions compared to the fossil fuel alternative [28]' rising to 80% for biomass systems installed after January 2026 [28]. The SRC willow riparian buffer strip system more than meets these requirements (95% reduction in base case), even when transportation distances rise to 250 km (91%). For truck transportation (including an empty return journey), distances could be further increased to about 942 km before GHG savings fall below 80% and 1576 km before they fell below 70%.

RED II also recommends that energy produced from biomass results in low indirect land use change (ILUC) impacts, with future limits to be set on bioenergy production systems incurring high ILUC impacts [28]. ILUC results when land for bioenergy fuels displaces land for food production, leading to the extension of agricultural land into other areas with high carbon stocks [28]. The GHG emissions associated with ILUC could potentially negate the GHG emissions savings of the bioenergy system [28]. In the case of SRC willow riparian buffer strips, the willow is planted on zones in which agricultural activities are already restricted, therefore, there is no displacement of agricultural land, thus avoiding any ILUC impacts.

SRC willow riparian buffer systems can also help countries meet water quality requirements such as those set out by the EU Water Framework Directive [3]. During growth, the willow absorbs excess nutrients from agricultural run-off. These nutrients are then removed from the agricultural system via harvest, permanently preventing them from entering and damaging the ecological status of local water bodies. Failure to adequately protect local water bodies could lead to an enforced reduction in agricultural output and a reduction in Common Agricultural Policy funding [60]. Thus, for policy makers, an SRC willow riparian buffer strip presents a win, win, win scenario in which significant GHG emission reductions are achieved, with no impact on agriculture while protecting local water bodies. Furthermore, while not assessed in this research, the inclusion of SRC willow in agricultural monocultures is expected to have a positive impact on biodiversity [61] helping to stave the alarming loss in biodiversity currently seen across the EU [62].

3.8. Limitations and future research

Economic analysis was outside the scope of this research, but a detailed analysis of the economic impact of the system is vital to understand the feasibility on a regional or national scale. An economic analysis would also provide valuable information for determining the best harvesting method to use. While the biobaler performs the best from an environmental and energy production perspective, it is typically much more expensive (€115,000 [63]) than a side harvester (€46,000 [43]), though still cheaper than a full stem harvester (€215,000 [43]). Furthermore, due to their size and shape, biobales require a specialised bale boiler and cannot be used in a standard biomass boiler – this could lead to further capital expenditure. Further studies could also look at the environmental and economic impact of alternative transport fuels such as biodiesel and the replacement or partial replacement of synthetic fertilizer with the ash produced by willow combustion.

There are also limitations using the GWP as the sole metric for evaluating the climate impact of the system. The choice of time horizon (100 years in this study) is subjective and affects the potency of different GHGs [64], while the impact of time-variable GHG fluxes are ignored if the net emissions are 0 (as with biomass fuels) [59]. Future work considering the temporal climate impact of the system would give an even clearer indication of the climate impact of the system. Further work could also investigate the use of LiDAR (light detection and ranging) and geographic information systems (GIS) to pinpoint and quantify areas suitable for SRC willow riparian buffer strips to enable results to be applied to a specific farm or region [18].

4. Conclusions

The results of this research provide key information for agri-environmental policy makers. Through the removal of excess nutrients from the agricultural system, the use of an SRC willow riparian buffer strip can play an important role in protecting local ecosystems and water bodies. Furthermore, sizable reductions in GHG emissions (95% for the base case) are achieved if the willow chip produced is used to replace a fossil fuel heating system. While the base case only accounts for minor transportation distances (2 km), the sensitivity analysis shows that, from an environmental and energy production perspective, the system still performs very strongly over much larger distances (250 km), indicating its suitability for widespread implementation on a regional or national level. However, further research is recommended to determine the economic performance and to consider the temporal climate impact of the system to give a complete picture for agri-environmental policy makers.

Author contributions

David Livingstone: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft preparation, Visualization. Chris Johnston: Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. Gary Lyons: Writing – review & editing, Supervision. Simon Murray: Writing – review & editing, Supervision. Aoife Foley: Writing – review & editing, Supervision. Beatrice Smyth: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aoife Foley is a co-author on this paper and is Editor in Chief of RSER, she was blinded to this paper during the review process, and the paper was handled by [Insert once established], [Senior/Associate-delete as appropriate] Editor.

Acknowledgements

This Bryden Centre project is supported by the European Union's INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB). The views and opinions expressed in this paper do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB). The work was also supported by Queen's University Belfast and the Agri-Food and Biosciences Institute in Northern Ireland. The authors would like to thank the staff at AFBI Hillsborough and Loughgall for their work in the establishment, maintenance and analysis of the study site.

Appendix A

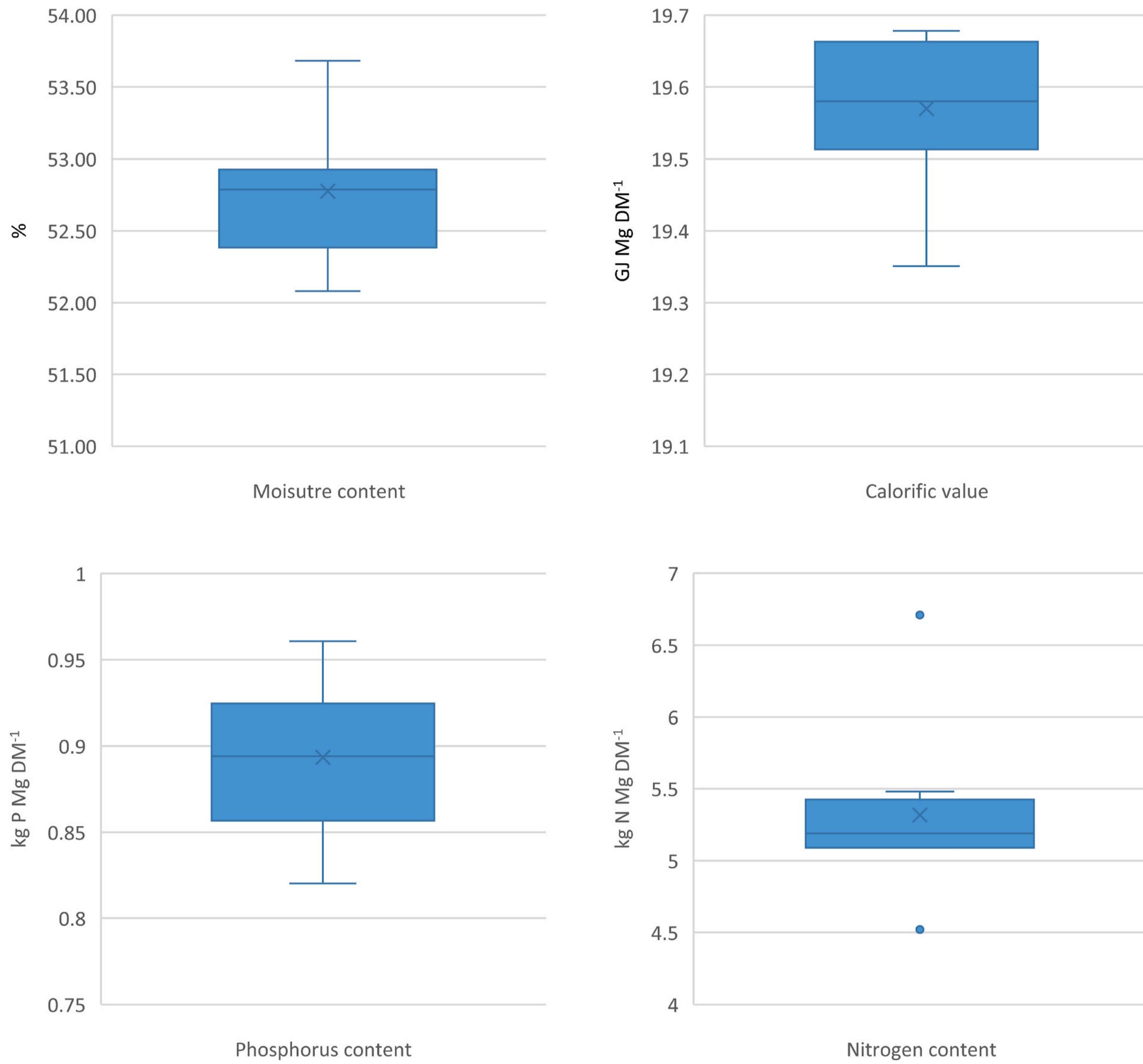

Fig. A1. Distribution of results for analysis of willow chip samples. The box represents the interquartile range (IQR), the horizontal line within the box represents the median, the cross represents the mean, the ends of the whiskers represent the highest and lowest value within 1.5 IQR and the points outside these are outliers.

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