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Production pathways for profitability and valuing ecosystem services for willow coppice in intensive agricultural applications

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ABSTRACT

Increasing agricultural sustainability is a key challenge facing the globe today. Energy crops, planted as riparian buffers are one way to support this, simultaneously mitigating water quality degradation and climate change. However, the economics of implementing such riparian buffer systems is under researched. Hence this work conducted a bottom-up economic analysis of willow coppice riparian buffers on a Northern Irish dairy farm, which is indicative of agricultural intensification across Europe. This work includes an economic assessment of a willow coppice riparian buffer strip, using harvested yield data from an established willow buffer site for the first time. It also considered the impact of harvesting technology on the economic performance of a willow coppice riparian buffer strip for the first time. The analysis considered three willow production pathways: 1) direct chip harvesting, 2) full-stem harvesting, and 3) a scenario with a guaranteed purchasing contract for fresh chip. Economic performance was considered using net present value over a 25-year plantation lifetime. The full-stem scenario provided the highest economic return over its lifetime with an average yearly net present value of £497 ha^{-1} (in £ sterling). This system was then considered for integration into a typical dairy farm, assuming 5 % land usage and including government grants for establishing riparian zones. The result was a drop in value of £28 ha^{-1} yr^{-1} compared to a dairy-only scenario; however, per litre of milk the farm employing willow coppice riparian buffer strips outperformed a typical dairy farm both environmentally and economically. Further analysis considered a novel approach that included payments for ecosystem services in the economic analysis. This analysis found that the implementation of government payments for ecosystem services (nutrient removal) increased the economic return of the willow coppice riparian buffer system by £400 ha^{-1} yr^{-1}, resulting in minimal impact on the return from dairy land.

1. Introduction

Agricultural production systems can no longer be singularly focussed on production efficiency. Instead there is increasing emphasis on agricultural sustainability (Jiang et al., 2022; Laurett et al., 2021). Short-rotation coppice (SRC) willow, planted as a riparian buffer in intensive agricultural settings has been suggested as one way to improve agricultural sustainability, simultaneously reducing on-farm greenhouse gas (GHG) emissions and water quality degradation, while minimising impact on food production (Livingstone et al., 2021). However, while increasing agricultural sustainability will have wide-ranging societal benefits, farmers still need to make a living. Therefore, understanding the economics of sustainability improvement measures is imperative.

Improving agricultural sustainability is one of the key challenges facing society as the demand for food continues to increase with rising global population. To meet these demands there has been a massive intensification of agricultural activities worldwide. However, as

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Nomenclature

Acronyms

AES	Agri-environmental scheme
AFBI	Agri-Food and Biosciences Institute
BPS	Basic payment scheme
C	Contract
DC	Direct chip
DM	Dry matter
EFS	Environmental farming scheme
EU	European Union
FS	Full-stem
GHG	Greenhouse gas
GVA	Gross value added
LPG	Liquified petroleum gas
LHV	Lower heating value
MC	Moisture content
NPV	Net present value
N	Nitrogen
NI	Northern Ireland
P	Phosphorus
RHI	Renewable Heat Incentive
SRC	Short rotation coppice
VAT	Value added tax
WWTP	Wastewater treatment plant

Symbols and units

CO_2eq	Carbon dioxide equivalents
€	Euro
GJ	Gigajoule
g	Grams
ha	Hectare
kg	Kilogram
km	Kilometre
kwh	Kilowatt hour
L	Litre
Mg	Megagram
MJ	Megajoule
m	Metre
p	Pence (sterling)
%	Percent
PO_4^{3-}	Phosphate
£	Pound sterling
yr	Year
t	Year

agricultural activities intensify there has been an associated increase in GHG emissions and environmental impacts on the natural environment. In fact, food production is responsible for approximately a quarter of global annual GHG emissions (Ritchie, 2020) and considerable reductions in these emissions are essential if the goal of the Paris Agreement is to be met (Leahy et al., 2020). At the same time nutrient run-off from agricultural activities is one of the leading causes of fresh water degradation in Europe, resulting in only 40 % of European Union (EU) surface water bodies (including the UK) achieving “Good or Better” ecological status in 2018 (European Environment Agency, 2018).

SRC willow riparian buffer strips are planted to intercept agricultural run-off before it enters local water bodies. Unlike conventional SRC willow plantations grown specifically for bioenergy, where fertiliser such as organic wastes might be used (González-García et al., 2014), the willow buffer is not directly fertilised, but instead use is made of the nutrients available in the agricultural run-off for growth (Agostini et al., 2021; Livingstone et al., 2021). The willow is then harvested as a renewable energy source to displace fossil fuel usage. By planting the willow in this way, biomass production can actually complement food production and competition over land use is limited (Christen and Dalgaard, 2013; Longato et al., 2019).

Previous research has found that the SRC willow riparian buffer system is an effective energy source with an energy ratio (the ratio of the energy put into the system compared to the energy provided by the system) ranging between 6.7 and 64, depending on the energy conversion pathway and buffer management practices (Agostini et al., 2021; Livingstone et al., 2022). Alongside energy production, the system also provides a slew of environmental benefits. These benefits can also be referred to as “ecosystem services” (Longato et al., 2019) or “non-market co-benefits” (Cathcart et al., 2021). Ecosystem services are defined as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life” (Daily et al., 1997) but they are often undervalued in decision making processes. Examples of the ecosystem services provided by the SRC willow riparian buffer strip system include: climate regulation through the reduction of GHG emissions and increases in soil carbon sequestration (Ferrarini et al., 2017), long term water quality protection through the permanent removal of excess nutrients (Livingstone et al., 2021), increased biodiversity (Bressler et al., 2017) and improved soil health (Zumpf et al., 2021).

While there is a growing amount of research into the environmental impacts of SRC willow riparian buffer strips, there is limited research into the economic viability of the system, which must be understood before large-scale implementation can be considered (Livingstone et al., 2021). In a review of conventional SRC willow plantations, Hauk et al. (2014) found that out of 37 reports, only 43 % showed economic viability. Only one paper was found in the literature investigating the economics of willow buffers (Ssegane et al., 2016). The study found that the willow buffer system economically outperformed the conventional system, due to the absence of fertiliser and headland requirements, but still resulted in net negative revenue returns due to high land rental costs. However, this work was limited, in that it was not based on an established willow buffer system and instead used assumed yields. The study also did not assess the economic impact of alternative willow production pathways such as direct chip harvesting, compared to full-stem harvesting.

To improve the economic performance of willow systems, the inclusion of a monetary value for ecosystem services has been suggested (Ferrarini et al., 2017; Ssegane et al., 2016). The valuation of ecosystem services is a growing area of research (Bressler et al., 2017), however applying a monetary value to such services has proven difficult in the past, due to the complexity of considering ecological components in economic models (Tagliafierro et al., 2013). To our knowledge no such monetisation has been assessed or included in an economic analysis of SRC willow riparian buffer strips to date, or in any system used to increase the sustainability of agriculture, indicating a key gap in the literature. Furthermore, helping policy makers to understand the monetary value of ecosystem services will aid the transition to more sustainable agricultural systems.

In Northern Ireland (NI) the agricultural sector is the largest emitter of GHGs and is responsible for 28 % of the region's total emissions (Committee on Climate Change, 2019). Northern Ireland's fresh water quality is also lower than the EU average, with only 31.4 % of surface water bodies achieving “Good or Better” ecological status, as defined by the EU Water Framework Directive (DAERA, 2018a). However, the agricultural sector is also vital to the Northern Irish economy and is responsible for 1.6 % of the gross value added (GVA) (DAERA, 2021). Therefore, reducing emissions and protecting water quality, with minimal disruption to the agricultural economy, is a pertinent issue in this region.

The aim of this work is to complete an economic assessment of an SRC willow riparian buffer strip located in an intensive agricultural setting, using data from an established willow buffer for the first time in the published literature. The work will also investigate, for the first time, the inclusion of monetary values for the ecosystem services provided and assess their impact on the economic value of the system. To do this, a hypothetical case study of an SRC willow riparian buffer strip site, established on a Northern Irish dairy farm, will be analysed to determine the economic return of the system and the most economical willow production pathway. Once this baseline economic assessment is completed, monetary values for ecosystem services will be applied to determine the overall value of the system.

The results will then be compared to those for a typical Northern Irish dairy farm and a Northern Irish dairy farm in which riparian zones had already been fenced off as part of an agri-environmental scheme (AES). While the results of this work focus on a Northern Irish dairy setting, the Irish dairy sector (both Northern Ireland and the Republic of Ireland) is representative of wider agricultural intensification across Europe (Balaine et al., 2020). The Irish dairy sector expanded by 33 % between 2010 and 2017 following the abolition of the milk quota (Balaine et al., 2020). The sector uses an intensive grass-based system, in which grassland is regularly fertilised (O'Brien et al., 2014), and has high stocking densities (the number of livestock units, e.g. cows, per ha of farmland) of around 2.1 (Adenuga et al., 2020). Furthermore, the SRC willow riparian buffer strip system is suitable for application across the continent, particularly in a northern temperate climate where willow yields are strong (Livingstone et al., 2021). The system can also be implemented in both pasture (Livingstone et al., 2022) and arable settings (Agostini et al., 2021), and so the results of this work should be of broad interest to the wider agri-environmental community.

2. Materials and methods

2.1. System description and site selection

In this research a hypothetical buffer system is analysed, however, real world data is used for the yield. The SRC willow riparian buffer strip was assumed to be established in 2020 and according to the "SRC Willow Best Practice Guidelines" for the island of Ireland (Teagasc and AFBI, 2015) but with reduced herbicide usage and no fertiliser inputs as described in Livingstone et al. (2022). Once established the site was assumed to be cut back after one year to encourage the growth of multiple shoots and ultimately increase the willow yield (Teagasc and AFBI, 2015). The site was then assumed to be harvested every three years (Fig. 1).

The yield was taken as 78.54 Mg ha^{-1} of fresh matter (55 % moisture content (MC)) for each three-year harvest, or 35.34 Mg dry matter (DM) ha^{-1}. This was based on an experimental site established by the Agri-Food and Biosciences Institute (AFBI) on their research farm in Hillsborough, Northern Ireland (Livingstone et al., 2022). The site incorporates three willow buffer plots, which were harvested in February 2020. The yield used in this research is the average of the three plots and accounts for 10 % losses for mechanical harvest. The harvest cycle was assumed to repeat seven more times, with a constant yield, before plantation termination using a mulcher, giving an overall plantation lifetime of 25 years.

2.2. Economic evaluation

Nominal gross margin and net present value (NPV) were used to assess the potential economic viability of the SRC willow riparian buffer strip. The nominal gross margin was taken as the difference between income and cost of willow chip production in any given year (t) (Eq. (1)), including the effect of inflation. As 72 % of all farms in Northern Ireland are owner-occupied (NISRA, 2021), it was assumed that the land would be already owned by the dairy farmers, therefore, the cost of land was excluded from calculations. The total gross margin (Eq. (2)) and average yearly gross margin were also calculated (Eq. (3)). Note that values are in £ sterling.

$$\textit{Nominal gross margin}_t\ (£) = \textit{Income}_t\ (£) - \textit{Costs}_t\ (£) \tag{1}$$

$$\textit{Total gross margin}\ (£) = \sum_{t=1}^{t=25} \textit{Nominal gross margin}_t\ (£) \tag{2}$$

$$\textit{Average yearly gross margin}\ (£) = \frac{\textit{Total gross margin}\ (£)}{25} \tag{3}$$

NPV was used as it accounts for the time value of money, with money earned in the early years considered to be more valuable than in the latter years of the project (Sinnott, 1999). In this method the net cash flow of each year, based on the gross margin of that year, is brought to its present value at the start of the project using a discount rate (Sinnott, 1999). The discount rate used in this work was 3.5 % as suggested by the UK central government guidance on appraisal and evaluation (HM Treasury, 2020). Again, the yearly NPV, for year t of the study (Eq. (4)), total NPV (Eq. (5)) and average yearly NPV (Eq. (6)) were calculated.

$$NPV_t(£) = \frac{\textit{Nominal gross margin}_t\ (£)}{(1+3.5\%)^t} \tag{4}$$

$$\textit{Total NPV}\ (£) = \sum_{t=1}^{t=25} NPV_t \tag{5}$$

$$\textit{Average yearly NPV}\ (£) = \frac{\textit{Total NPV}\ (£)}{25} \tag{6}$$

2.3. Determining the optimum production pathway for willow riparian buffers

Three alternative harvest scenarios commonly used on the island of Ireland were initially assessed to obtain the most economically viable

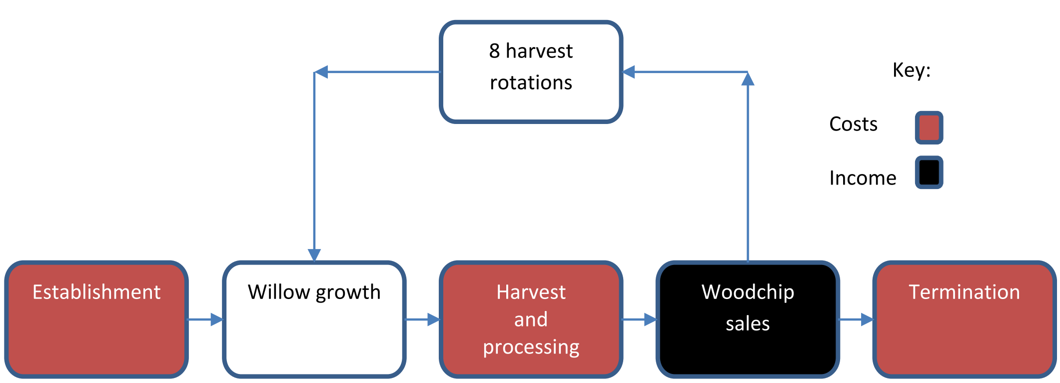

Fig. 1. Lifecycle overview of willow riparian buffer strip.

pathway for willow chip production. The most economically viable pathway was then described as the optimum production pathway throughout the rest of the paper. In each scenario, the yield and establishment costs were assumed to remain the same (Table 1). Once the optimum production pathway was obtained, a sensitivity analysis was undertaken to determine the impact of yield and willow biomass selling price.

2.3.1. Direct chip harvesting (Scenario DC)

In the first scenario, direct chip harvesting was assumed (Scenario DC). Once harvested, the fresh willow chip was assumed to be transported to dedicated drying facilities where ventilated grain drying floors were used to dry the willow chip to 20 % MC (Teagasc and AFBI, 2015). It was assumed that the drying facilities were 20 km from the farm, which is the maximum recommended transportation distance for willow chip (Teagasc and AFBI, 2015). Once dried, the willow chip was assumed to be transported back to the farm to be sold from the farm gate at a price of £100 Mg^{-1} of willow chip at 20 % MC (personal communication with local willow supplier).

Transportation was assumed to be completed by truck with a walking floor trailer, as the environmental impacts of truck transport are significantly lower than those of a tractor and trailer (Murphy et al., 2014) and walking floor trailers have a much larger bulk capacity than tipper trailers. The maximum loads for walking floor trailers are typically 25 Mg for fresh willow chip (55 % MC) and 15 Mg for dry willow chip (20 % MC) (personal communication with local willow supplier). With a yield of 78.54 Mg ha^{-1} of fresh matter, four truckloads are required to transport a hectare worth of willow to the drying facilities. Once dried to 20 % MC, the willow would require three truckloads for transport back to the farm. With a transport cost of £1.78 km^{-1} (personal communication with local willow supplier), this results in total transportation costs of just under £250 ha^{-1} $harvest^{-1}$, which is assumed to rise with inflation (using the Bank of England database (Bank of England, 2021b)) throughout the plantation lifetime (Table 1).

2.3.2. Full-stem harvesting (Scenario FS)

For the second scenario (Scenario FS), an alternative harvesting technique was considered in which full-stem harvesting was employed instead of direct chip. In this case, artificial drying is not required but an additional stage for chipping is needed (Teagasc and AFBI, 2015). The harvest and chipping costs for full-stem harvesting were taken from the "Best Practice Guidelines" for the island of Ireland, and adjusted for currency and inflation using the Bank of England databases (Bank of England, 2021a, 2021b) (Table 1). For this scenario the price of woodchip was assumed to be the same as for Scenario DC (£100 Mg^{-1} for willow chip at 20 % MC).

2.3.3. Contract with power station (Scenario C)

The third production scenario (Scenario C) considered a contract situation in which the farmer and a local power station commit to a long-term selling agreement. There are currently no large-scale power stations using biomass as a fuel source in Northern Ireland, therefore this scenario was based on a recent scheme run in the Republic of Ireland. In this scheme, a local power supplier (Bord na Móna) offered to pay willow growers within 100 km of any of its power stations up to €38 Mg^{-1} fresh chip ex-gate (Irish Examiner, 2010). They also promised to cover half of the establishment costs. Exchanging the price into pound sterling (1.17€/£ in 2010 (Bank of England, 2021a)) and adjusting for inflation (average inflation 2010–2020 1.3 % (Bank of England, 2021b)) results in a price of £42.71 Mg^{-1} fresh willow chip. The willow was assumed to be harvested via direct chip, as in Scenario DC, however, as the chip is sold fresh from the farm gate, there were no drying or transport costs.

2.4. Cost data and assumptions

Costs for each scenario were sourced from the literature and personal communications with local business owners (Table 1). All activities and materials required throughout the life cycle of the plantation were costed from establishment in 2020 to termination in 2045. It was assumed that all activities were carried out by a local external contractor, therefore no capital costs for machinery were included. The yearly rate of inflation was taken as 2.5 % based on the Bank of England average for the last five years (Bank of England, 2021b). Exchange rates were taken from the Bank of England database for costs sourced from the literature, based on the year of publication (Bank of England, 2021a). Value-added tax (VAT) for field activities and willow cuttings was taken as 13.5 % and VAT for herbicide purchase was taken as 21 % (Teagasc and AFBI, 2015).

Costs were calculated on a basis of one hectare of willow chip production, per GJ of energy stored in the dried willow chip (20 % MC) and per Mg of willow chip produced. The lower heating value (LHV) for the willow chip produced was taken as 17.4 MJ kg^{-1} DM at 20 % MC (Livingstone et al., 2022), giving a total energy production of 614

Table 1
Costs for willow chip production.

Life cycle stage	Activity	Cost[a]	Units	Scenario[d]	Source
Establishment[b]	Herbicide spraying	24.68	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
	Ploughing	92.57	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
	Harrowing	98.74	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
	Planting	431.98	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
	Rolling	12.34	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
	Cutback	37.03	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
Willow chip processing	Direct chip harvesting	30.86	£ Mg DM^{-1}	DC, C	(Teagasc and AFBI, 2015)
	Drying	47.72	£ Mg DM^{-1}	DC	(Personal communication with local willow supplier)
	Transport	249	£ ha^{-1}	DC	(Personal communication with local willow supplier)
	Full-stem harvesting	37.03	£ Mg DM^{-1}	FS	(Teagasc and AFBI, 2015)
	Chipping	8.23	£ Mg fresh $chip^{-1}$	FS	(Teagasc and AFBI, 2015)
Termination	Mulching	98.74	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
Materials		Cost £			Source
Willow cuttings		1563.34	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)
Glyphosate[c]		32.91	£ ha^{-1}	DC, FS, C	(Teagasc and AFBI, 2015)

Note.
[a] Costs as of 2020 excluding VAT.
[b] Establishment costs for Scenario C were halved due to payment by powerplant.
[c] Four litres of glyphosate required per hectare for pre-plough herbicide spray only (Livingstone et al., 2022).
[d] DC = direct chip, FS = full-stem, C = contract.

GJ ha^{-1} per harvest. It was assumed that a loan was required to cover the cost of establishment. This loan was assumed to be paid back over five years with an interest rate of 6 %, assuming that the loan was secured (Bank of Ireland UK, 2021, personal communication; Ulster Bank, 2021, personal communication). Field activities, such as establishment and harvest, are expected to cost more per unit area for buffer strips than for conventional plantations, as the willow would be planted in smaller areas spread across different sections of the farm (Börjesson, 1999). The amount by which these costs will increase depends on the size and shape of each buffer plot, and the distance between plots, and would change on a case-by-case basis. For this study, the costs of all field activities were increased by 50 %. This is in line with the cost increase suggested in the farm management handbook for farming activities on smaller fields (SAC Consulting, 2018).

2.5. Whole-farm comparisons (Scenarios 4, 5 and 6)

The optimum production pathway was then used as the basis for whole-farm comparisons. Three farm scenarios were considered: a typical Northern Irish dairy farm (Scenario 4), an AES (agri-environmental scheme) Northern Irish dairy farm with riparian areas fenced off but left unmanaged (Scenario 5), and an AES Northern Irish dairy farm with SRC willow riparian buffer strips planted on already fenced-off land (Scenario 6). The gross margin for the typical Northern Irish dairy farm (Scenario 4) was taken as £1537 ha^{-1} yr^{-1}, assuming a typical yield and average calving pattern and ignoring area-based payments (DAERA, 2020b), and it was assumed that no land was given to riparian protection. Area-based payments, such as the Basic Payment Scheme (BPS), were not included in the calculation for gross margin of any scenario as these would be unaffected by the implementation of the willow buffers (DAERA, 2020a).

For the other two farm scenarios (Scenarios 5 and 6), it was assumed that 5 % of all dairy land was fenced off as buffer strips to provide adequate riparian protection while minimising the impact on dairy output (Livingstone et al., 2021). A loss of dairy income of 5 % was assumed for these scenarios due to a 5 % loss of forage, resulting in an assumed loss of milk yield of 5 %. The recommended width for buffers is 10 m (Buckley et al., 2012), and a length of 50 m for each hectare of farmland was assumed, resulting in an area of 500 m^2 (5% of 1 ha). For the AES farm (Scenario 5), these strips were assumed to be unmanaged.

There are currently no government incentives directly related to the use of energy crops as riparian buffers in Northern Ireland, but incentives are available for the creation of unmanaged buffer strips as part of the Environmental Farming Scheme (EFS) (DAERA, 2020a). These payments last five years and for 10 m wide buffers are £7.63 m^{-1} in the first year and £0.36 m^{-1} in years 2–5 (DAERA, 2020a). For a length of 50 m this equates to £381.5 ha^{-1} of farmland in year 1 and £18 ha^{-1} of farmland in years 2–5. This money was added into the calculations for the gross margin for the two AES scenarios (Scenarios 5 and 6) and more than covers the 5 % loss in dairy income (£76.85 ha^{-1} yr^{-1}) for the five years the EFS scheme runs.

For Scenario 6, the gross margin of the willow buffers was included alongside dairy income and any income from the EFS. The gross margin from the willow was 5 % of that calculated in the initial analysis of the optimum production pathway, due to the land split (95 % dairy, 5 % willow). In this scenario it was assumed that no loan would be required as the cost of establishment would be covered by the money from the EFS. The gross margins in all cases were adjusted for inflation over the course of the 25-year willow plantation lifetime and used to calculate the NPV for each scenario.

2.6. Valuation of ecosystem services

A further scenario was also considered (Scenario 7), taking into account the impact of additional income via the monetisation of ecosystem services. There are three main aims of the SRC willow riparian buffer strip system: water quality protection, reducing the climate impact of agriculture, and renewable energy generation. Due to the high GHG emissions associated with agriculture (Ritchie, 2020), it is currently unlikely that farmers would be paid for carbon abatement, especially the short-term carbon abatement associated with energy crops. Therefore, the only ecosystem service monetised in this research was nutrient removal (Scenario 7, Table 2). This scenario was assumed to take place on an AES farm.

2.6.1. Nutrient removal

The income from nutrient removal was based on the permanent removal of nutrients via willow harvest. The nutrients considered were nitrogen (N) and phosphorus (P), as nitrates and phosphates are the main contributors to the degradation of local water bodies via eutrophication. The willow at the AFBI site was assessed for its total N and P content once harvested. The values obtained were 0.9 kg P Mg^{-1} DM and 5.3 kg N Mg^{-1} DM (Livingstone et al., 2022), which equates to 31.81 kg P ha^{-1} of willow harvest and 187.32 kg N ha^{-1} of willow harvest. These values were used as the basis for all calculations on income for water quality protection.

The true cost of P and N removal is difficult to quantify as the extent of damage caused by the nutrients will vary greatly depending on the current state of the local environment. Therefore, the cost of P and N removal in wastewater treatment plants (WWTP) was considered as a proxy. The cost of removing P and N in Northern Irish WWTPs has been calculated to range between £5.8 and £14.8 kg^{-1} N removed, depending on the size of the WWTP and infrastructure in place (Rosenqvist and Dawson, 2005). These values include the cost of P removal. For the current research, the value of nutrient removal was conservatively based on the low price, which, adjusted for inflation, equates to £8.86 kg^{-1} N removed. This value was multiplied by the amount of N removed at each harvest, giving a total income from N and P removed of £1660 ha^{-1} $harvest^{-1}$ for each hectare of willow buffer (£83 ha^{-1} of

Table 2
Scenarios summary.

Scenario[a]	Land use	Willow production pathway	Willow price[b] £ Mg^{-1}	Further description
Assessment of willow riparian buffers on a per ha basis to find optimum willow production pathway				
DC	100 % willow	Direct chip, drying	100	N/A
FS	100 % willow	Full-stem	100	N/A
C	100 % willow	Direct chip, no drying	42.71	N/A
Whole-farm comparisons of dairy, dairy AES, and dairy with riparian buffers				
4	100 % dairy	N/A	N/A	Typical dairy farm scenario
5	95 % dairy, 5 % unmanaged buffer	Optimum[c]	N/A	AES dairy farm
6	95 % dairy, 5 % willow	Optimum[c]	100	AES dairy farm with willow
7	95 % dairy, 5 % willow	Optimum[c]	100	AES dairy farm with willow, including the value of nutrient removal

Note: a. Full scenario details given in Sections 2.3–2.6. b. Price for willow chip at 20 % MC in all cases except Scenario C where the price is for willow chip at 55 % MC. c Optimum production pathway is the most economically viable production pathway. DC = direct chip, FS = full-stem, C = contract, AES = agri-environmental scheme.

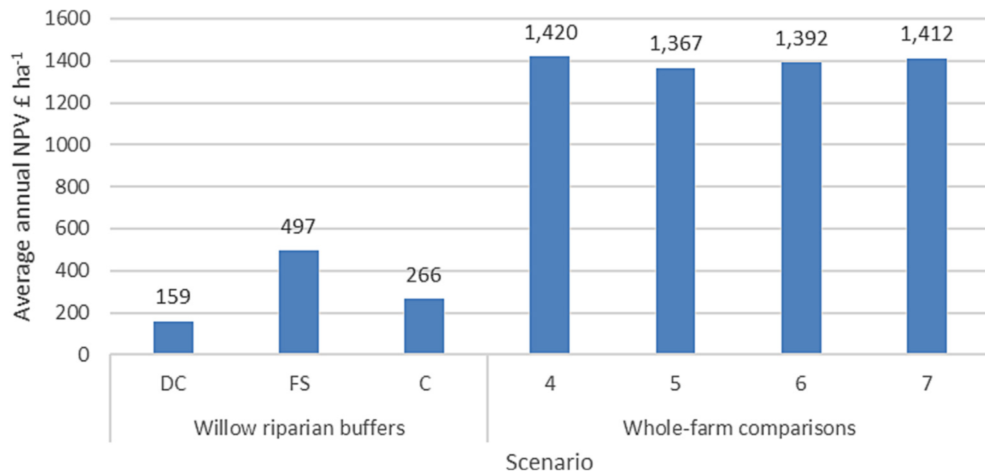

Fig. 2. Average yearly NPV per ha of willow riparian buffer and per ha of dairy farm (whole farm comparison) under different willow riparian buffer scenarios. Scenario DC = direct chip harvesting; FS = full-stem harvesting; C = guaranteed purchasing contract for fresh chip; 4 = dairy only; 5 = dairy plus unmanaged riparian buffer; 6 = dairy plus willow riparian buffer; 7 = dairy plus willow riparian buffer with nutrient removal payments.

total farmland). It was assumed that all of this money would be paid to the farmer at each harvest once EFS payments had ceased (after year 5), representing a redistribution of public money from wastewater treatment to farmers. While this does not necessarily save money for the public, there are other, non-monetary benefits of this redistribution, such as increased biodiversity (Bressler et al., 2017) and improved soil health (Zumpf et al., 2021). Furthermore, by preventing the pollution at its source, rather than the nearest water treatment works, any ecological damage which may have occurred downstream of the run-off prior to the water treatment works is avoided. The impact of nutrient leakage from the water treatment works, which are not 100 % efficient, is also avoided.

3. Results and discussion

3.1. Scenario comparisons

All three scenarios result in positive returns with Scenario FS (full-stem harvesting) showing the greatest economic viability over the course of the plantation lifetime (Fig. 2). The main disadvantage of Scenario DC (direct chip) is the drying requirements, which, coupled with transportation to and from the drying facilities, make up the majority of the total costs for this scenario (Fig. 3). Furthermore, the minimum batch amount for commercial woodchip drying is 100 Mg of fresh matter (personal communication with local willow supplier). Therefore, more than one hectare of willow buffer (1.3 ha) is needed to meet this requirement for the per hectare yield assumed in this study. With only 5 % of farmland assumed to be used for willow plantations, a minimum farm size of 26 ha is required before Scenario DC is feasible, assuming a stocking density of 2.1 (Adenuga et al., 2020); this excludes around 30 % of the dairy farms in Northern Ireland (DAERA, 2022). This limitation does not exist for the full-stem (Scenario FS) and contract (Scenario C) scenarios as no drying is required, significantly reducing the overall costs for these scenarios (Fig. 3). While Scenario FS does have added chipping costs, these are far smaller than the costs for drying fresh woodchip (£7503 ha^{-1} compared to £19,582 ha^{-1} over the plantation lifetime). Scenario C has the lowest overall cost but is not as profitable as Scenario FS due to the lower price for fresh willow chip compared to dry willow chip. The price per Mg of wood chip produced was £108 Mg^{-1} (£38,407 ha^{-1}, Fig. 3) and £78 Mg^{-1} (£25,972 ha^{-1}, Fig. 3) of willow chip at 20 % MC (lifetime yield 353 Mg ha^{-1}) for Scenario DC and

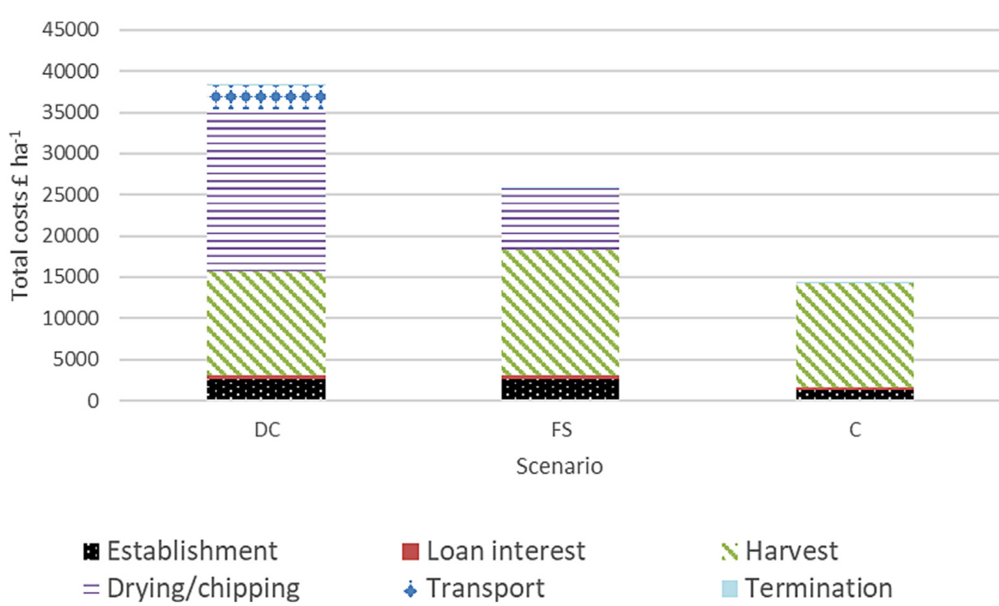

Fig. 3. Lifetime costs per hectare for three willow production pathways: direct chip harvesting (Scenario DC), full-stem harvesting (Scenario FS), and guaranteed purchasing contract for fresh chip (Scenario C).

Scenario FS respectively, and £23 Mg^{-1} (£14,391 ha^{-1}, Fig. 3) of willow chip at 55 % MC for Scenario C (lifetime yield 628 Mg ha^{-1}).

Aside from overall profitability there are other factors that need to be considered. With the lowest costs, Scenario C presents the lowest risk to farmers. The long-term contracts provided in Scenario C also guarantee an income, unlike for Scenario FS and Scenario DC which are dependent on the local biomass market. With reduced establishment costs, Scenario C also sees the quickest payback time (Fig. 4), breaking even after four years, more than twice as quick as Scenario DC and three years faster than Scenario FS. There are also no on-farm storage requirements in Scenario C for willow chip or stems, as the chip would be sold directly from harvest. However, while there is less risk involved with Scenario C, there is more potential reward in Scenario FS and, if biomass prices were to rise in the coming years, the fixed prices for Scenario C could become a disadvantage in the long term. Previous research by the authors (Livingstone et al., 2022) found that full-stem harvesting also significantly outperforms direct chip harvesting in terms of energy ratio and emissions reductions, therefore this mode of harvest is recommended and was the production system used when calculating the impact of ecosystem service payments and for the sensitivity analysis (optimum production pathway).

The positive returns for each scenario in this research are in contrast to the findings of a US study by Ssegane et al. (2016), who found the SRC willow riparian buffer system to have net negative revenue returns. They calculated net revenue as the yearly income minus yearly costs and did not account for inflation. Using their methodology (subtracting yearly costs from yearly income and ignoring inflation), the net revenue for the three scenarios studied in this current paper was still positive, at £195 ha^{-1} yr^{-1} for Scenario DC, £584 ha^{-1} yr^{-1} for Scenario FS and £303 ha^{-1} yr^{-1} for Scenario C. One reason for the low returns in Ssegane et al. (2016) was the inclusion of high land rental rates. In the current paper, land costs were ignored. If land rental costs were included, the net revenue for each scenario would drop by £142 ha^{-1} yr^{-1} on average. This is based on the highest conacre rental charges for Northern Irish dairy farms reported by the Department of Agriculture and Rural Affairs (DAERA) (DAERA, 2020b). A conacre is an area of land farmed under a short term letting arrangement in Ireland (DAERA, 2018b). The highest land rental price used in Ssegane et al. was \$227 $acre^{-1}$ for the year 2013. Using the exchange rate of the time and adjusting for inflation this equates to £419 ha^{-1} yr^{-1}, almost three times the land cost for Northern Ireland, and would result in all but Scenario FS producing a net negative return. This would be an unrealistic scenario in the current context in Northern Ireland but highlights the importance of region-specific cost differences on the economic outcome.

3.2. Sensitivity analysis

A sensitivity analysis was undertaken to discern whether the willow yield or selling price had a greater impact on the overall NPV of the system for Scenario FS. To do this the willow yield and selling price were independently decreased and the resulting decrease in NPV determined. Looking at the impact of willow price and yield on Scenario FS, it can be seen that the system is more sensitive to a change in willow chip price (Fig. 5), with the system no longer returning a positive NPV once the price drops by 40 % (£60 Mg^{-1} for willow chip at 20 % MC). Compared to this, even with a 47 % reduction in yield (6 Mg DM ha^{-1} yr^{-1}), which is the lowest yield expected for Northern Irish conditions (Teagasc and AFBI, 2015), the system provides positive economic returns.

3.3. Whole-farm comparison

While all of the scenarios described here present a loss of income if replacing active dairy land (Fig. 2), when the willow was planted on an already existing but unmanaged riparian buffer strip as part of the EFS scheme, it provides an excellent opportunity for extra revenue for the farmer. This is especially the case as the income from the EFS scheme ends after five years, while the willow provides income for up to 25 years. Furthermore, the income provided in the first year of the EFS scheme is enough to cover the willow establishment costs,

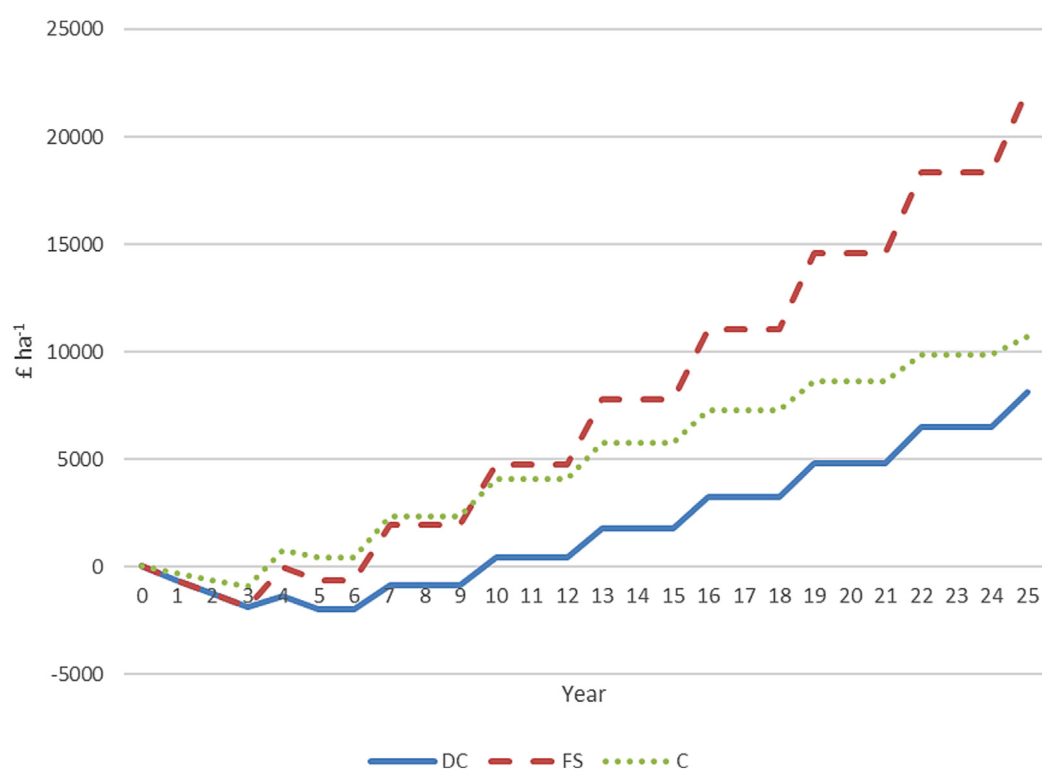

Fig. 4. Cumulative gross margin per hectare for three willow production pathways: direct chip harvesting (Scenario DC), full-stem harvesting (Scenario FS), and guaranteed purchasing contract for fresh chip (Scenario C).

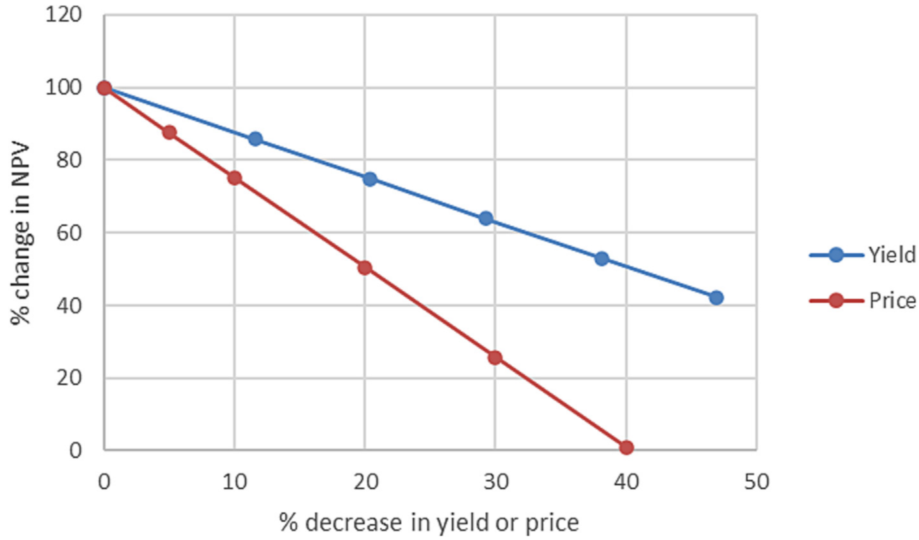

Fig. 5. Sensitivity analysis for changes to willow yield and willow price compared to the base-case Scenario FS (full-stem harvesting). Note: NPV = net present value.

eliminating the need for a loan and nullifying the risk to farmers. The willow will also enhance the water quality protection provided by the buffer strip, as unmanaged buffers have been shown to become ineffective once they become saturated with nutrients (Hénault-Ethier et al., 2018). In comparison, the SRC willow riparian buffer strip system provides long-term water quality protection due to regular harvests which permanently remove nutrients from the agricultural system and prevent saturation of the buffer.

Adding the income from water quality protection (Scenario 7) significantly improves the economic return for the full-stem scenario with the average annual NPV rising by £20 ha^{-1} of farmland yr^{-1}. This helps to bridge the gap with dairy farming, resulting in a difference in NPV of just £8 ha^{-1} of farmland yr^{-1} on average for Scenario 7 compared to the typical dairy scenario (Scenario 4). However, the value for water quality protection is based on the farmer being paid up to the alternative cost for conventional treatment, while in practice these payments are likely to be slightly lower as wider society would also try to profit from the reduced costs to water treatment (Rosenqvist and Dawson, 2005).

While the typical dairy scenario (Scenario 4) still provides the best economic return per ha, the environmental impacts of this scenario are the worst. Furthermore, when comparing economic return per litre of milk, the AES farm with willow buffers (Scenario 6) actually outperforms the typical dairy scenario (Scenario 4) even without additional income for water quality protection services (Table 3). Assuming that the willow chip is used to displace oil-fired heating, GHG emissions for Scenario 6 are also 12 % lower per litre of milk than for Scenario 4 (Table 3). Furthermore, excess nutrients that have the potential to cause eutrophication in local water bodies are reduced by 11 % (Table 3).

3.4. Comparison with other fuels

It is assumed that the dried willow chip (20 % MC) produced by the FS production system would be used to power biomass boilers for commercial heating purposes. Assuming a conversion efficiency of 85 % (Livingstone et al., 2022), the willow chip produced could provide 4182 GJ ha^{-1} of heat output over the plantation lifetime. With a purchase price of £100 Mg^{-1} of willow chip at 20 % MC content and taking into account inflation over the plantation lifetime, this equates to an average retail cost of 4.4 pence (p) kWh^{-1} of heat produced for the willow chip customer. If the chip is used on site for the farmer's heating requirements, such as heating water for the milking parlour, the average production cost is 2.7 p kWh^{-1}. This compares well with the cost for commercial heating of other sources on the island of Ireland (Table 4).

For the contract scenario (Scenario C), the fresh willow chip would be burned in a power station to produce electricity. In this case, the LHV per unit mass would be lower, due to the higher MC. Using the methodology set out in Hammar et al. (2017), the LHV for willow chip at 55 % MC is 15 GJ Mg^{-1} DM, meaning 4241 GJ ha^{-1} of energy stored in the willow chip would be provided to the power station over the plantation lifetime, costing 2.28 p kWh^{-1} energy delivered. Assuming an electrical conversion efficiency of 36 % (European Commission, 2018), this equates to 6.33 p kWh^{-1} of electrical energy produced. The average cost to the consumer of electricity in Northern Ireland currently (January 2023) sits around 25 p kWh^{-1} excluding VAT(The Consumer Council, 2023).

3.5. Further discussion

There are further ecosystem services provided by an SRC willow riparian buffer strip that add value and, therefore, could also be considered for monetisation. The integration of the willow buffer is expected to result in an increase in biodiversity by supporting pollinator species and splitting up a monoculture of grass (Bressler et al., 2017; Christen and Dalgaard, 2013; Ferrarini et al., 2017), as well as resulting in improved soil health (Ferrarini et al., 2017; Zumpf et al., 2021) and reduced soil heavy metal loads (Börjesson, 1999; Rosenqvist and Dawson, 2005). If strategically placed, SRC willow buffers can also alleviate flood risk (Christen and Dalgaard, 2013) and reduce bank and soil erosion (Bressler et al., 2017). While these positive impacts are

Table 3
Comparing the economic and environmental impacts of Scenarios 4 and 6.

Impact category	Scenario 4 (Typical dairy)	Scenario 6 (Dairy AES with willow)	Reference
Amount of milk L ha^{-1}	14,779	14,040	(DAERA, 2020b)
Average yearly NPV p L^{-1}	9.6	9.9	Current research
GHG emissions g CO_2eq L^{-1}	575	506	(Livingstone et al., 2021)
Nutrient excess g PO_4^{3-} L^{-1}	2.97	2.65	(Livingstone et al., 2021)

Note: AES = agri-environmental scheme, NPV = net present value, GHG = greenhouse gas, p = pence (sterling).

Table 4
Commercial heating fuel prices in Ireland compared to the retail cost for heat from willow.

Fuel type	Conversion efficiency %	Cost[a] p kWh_{heat}^{-1}
Willow	85	4.4
Oil[b]	70	9.67–11.45
LPG[c]	90	9.07–14.34
Gas	90	2.65–4.60
Electricity	100	7.17–24.04
Wood pellets	85[d]	5.46–6.59
Electricity for heat pumps	N/A	1.31–9.62

Note.
[a] Prices and efficiencies (unless otherwise stated) as of October 2021 (SEAI, 2021), exchange rate for euro to sterling taken from Bank of England database for October 2021 (Bank of England, 2021a).
[b] Assuming a standard oil-fired boiler.
[c] Assuming a condensing boiler, LPG = liquified petroleum gas.
[d] Efficiency for biomass boiler taken from Livingstone et al. (2022).

observable, they are difficult to quantify and place a monetary value on. Therefore, they were considered to be beyond the scope of this current study. However, this evidence could be taken into account by the public sector when establishing if and how to support SRC willow buffers, as there is a public benefit.

Furthermore, while payments to farms for carbon abatement currently look unlikely, there is increasing pressure on the UK government to introduce a GHG tax for meat and dairy produce (Hawkins, 2021). The integration of SRC willow riparian buffer strips could reduce Northern Irish dairy farm GHG emissions by around 16.5 % by displacing oil-based energy and, if farmers maintain their current stocking-densities, 5 % lower cattle numbers (Livingstone et al., 2021). Dairy cattle numbers have increased dramatically in recent years, so a 5 % reduction would only bring them back to 2014/15 levels in NI (DAERA, 2015). A carbon tax of £50 per Mg of CO_2eq has recently been suggested to help the UK reach net zero by 2050 (Burke et al., 2020). If this value were considered, an emissions reduction of 16.5 % could save a Northern Irish dairy farmer about £70 ha^{-1} yr^{-1} assuming GHG emissions of 8.5 Mg ha^{-1} yr^{-1} (Buckley et al., 2019) prior to willow planting.

This reduction in GHGs could also represent a significant cost saving to farmers if mechanisms are introduced to incentivise lower emissions embedded in food (such as certification and labelling schemes in domestic markets, and some adjustment at the border for foreign markets). In this case, while not receiving a direct income for avoiding GHG emissions associated with primary agriculture, the SRC willow riparian buffer system could indirectly increase the farm's economic performance by improving the farm GHG footprint, opening-up access to price premiums for climate-friendly produce.

Widespread implementation of SRC willow riparian buffer systems also presents opportunities for the social economy. The Northern Irish biomass industry is currently languishing (personal communication with local willow supplier) after an unsuccessful renewable heat incentive (RHI) scheme (McDowall and Britchfield, 2021). The result of this failure has meant there is currently no supporting mechanism for low-carbon heat in residential or industrial settings (Committee on Climate Change, 2019), leading to a sharp decline in local biomass suppliers (personal communication with local willow supplier). Including government payments for ecosystem services could help reinvigorate this indigenous industry, reducing the risk to farmers by reducing payback times and increasing income. This would have a knock-on effect of creating new jobs along the biomass supply chain and help the local economy twofold: by producing indigenous energy supplies and reducing reliance on imported energy sources.

3.6. Limitations and further work

While the methodology followed in this paper can be widely applied, many of the costs are specific to conditions on the island of Ireland (Northern Ireland and the Republic of Ireland) and in the UK. This is also true of the valuation placed on N and P removal from WWTPs. Therefore, countries outside these regions would need to consider country-specific costs when assessing the potential economic impact of implementing SRC willow riparian buffer strips in their region. For the local context, the values presented here are not definitive for all circumstances, but offer a guide price on the return the system could provide based on the assumption of a local contractor carrying out all activities. If contractors are further away and the area for willow is relatively small (<2 ha), the price to reach the farm could be prohibitive (personal communication with local willow supplier), although this would need to be assessed on a farm-by-farm basis. Furthermore, for smaller areas where machine access is not available, establishing and harvesting the willow by hand may be more applicable; however this scenario was considered beyond the scope of the research. Another aspect to consider in future work is the option for farmers employing the willow buffer system to form a co-operative with other local growers which could help lower the overall costs of willow harvest.

A further scenario that could be assessed is the use of a biobaler for harvest. In previous research, the biobale harvesting system was calculated to have a higher energy ratio and greater potential to reduce GHGs than the full-stem scenario (Scenario FS) (Livingstone et al., 2022). However, biobale technology is relatively new to the island of Ireland; the costs associated with the system are unreported and so not included in this research. As with the full-stem scenario (Scenario FS), the biobales produced do not require artificial drying and can be left in the field to dry (covered or uncovered) (Dias et al., 2017). While the biobaler requires a tractor to pull it along, the combined system is much smaller than a direct chip or full-stem harvester, and so may be more applicable for harvesting small areas like a riparian buffer strip (Savoie et al., 2013). The downside of the system is that the bales are unchipped and therefore unsuitable for conventional biomass boilers (Livingstone et al., 2022); they would need to be burned in bale boilers or further processed prior to use. The biobales could also be burned in large-scale electric power stations. Future work investigating the costs associated with biobale harvest in Northern Ireland is recommended. Further research should also consider the impact of different harvest machinery on soil erosion and sediment losses into riparian areas.

Alongside this, work into the logistics of the system, such as the potential need for an inter-field road network, is recommended. Likewise research considering the infrastructure and supply chain requirements for widespread implementation in the region is also recommended, in particular the costs of large-scale biomass power generation and the amount of biomass required to fulfil generation needs. Further research into the value of other ecosystem services such as biodiversity increases, or heavy metals removal is also recommended. Future research could also investigate any potential ecosystem services related to animal well-being, for instance by providing wind protection and shaded areas and how this may impact milk yield depending on the initial severity of agricultural intensification.

4. Conclusions

This bottom-up economic analysis shows the value that SRC willow riparian buffer strips can add to the Northern Irish dairy industry as a case study of their sustainability and environmental potential in the farming sector. For the first time, the impact on the economic performance of an SRC willow riparian buffer strip system of harvesting technology is addressed. This is also the first time that: (i) real world data has been used in an economic assessment for an SRC willow riparian buffer strip and (ii) a monetary value for ecosystem services has been included in an economic analysis of any system used to increase the sustainability of agriculture. The results found that when planted on existing restricted land or marginal areas, the SRC riparian buffer systems present a win-win-win situation in which water quality protection is enhanced and GHG emissions are reduced, alongside the generation of a valuable income stream for farmers to encourage a shift to more sustainable agricultural practices.

Of the three harvest systems considered, 1) direct chip harvesting, 2) full-stem harvesting, and 3) a scenario with a guaranteed purchasing contract for fresh chip, the full-stem harvesting system was found to be the most economical, with an average yearly NPV of £497 ha^{-1} of willow. The sensitivity analysis found that the system is more reactive to price changes in the biomass market than willow yield.

Despite this strong return, with high upfront costs and a relatively long payback period, the implementation of such a system represents a risk to Northern Irish dairy farmers, especially if buffers are placed on active dairy land. Government incentives such as the EFS scheme in NI can eliminate some of this risk by covering the upfront costs of willow establishment. When comparing farms on a per litre of milk basis, a dairy farm employing SRC willow riparian buffer strips and making use of EFS payments outperforms a typical dairy farm both environmentally and economically. However, when comparing farms on a per hectare basis, a gap still remains between income from the buffer system and dairy land. Therefore, a novel approach, in which payments for ecosystem services were included in the economic analysis, was assessed. The results of this analysis found that the implementation of government payments for ecosystem services, through nutrient removal, greatly increased the economic return of the SRC willow riparian buffer system, resulting in minimal impact on the return from dairy land. These payments would also increase income certainty, as the ecosystem service payments are not reliant on the biomass market. Therefore, the overall risk to farmers is reduced and their willingness to adopt the measure should be increased.

In summary, this analysis highlights the value of riparian buffer systems and it is strongly recommended that government incentives schemes are introduced to promote sustainable farming practices, such as payments for ecosystem services to encourage local dairy farmers to implement SRC willow riparian buffer strips. It is clear that such schemes could help the agricultural sector meet the Water Framework Directive (European Commission, 2000) and renewable energy targets. Such incentive schemes would also stimulate local biomass markets and help reduce reliance on imported biomass, all the while increasing the sustainability of the agricultural sector. Future work is recommended 1) to investigate other case studies with riparian crops in other countries, 2) to further examine government and EU incentive schemes relevant to the development of these sustainable farming practices, and finally 3) to study the use of biobalers to harvest riparian crops, as well as to investigate the feasibility of large-scale biomass power generation to support local electricity needs and reduce dependency on imported fossil fuels such as coal and natural gas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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