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Willow short rotation coppice. Energy and environmental assessment

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ABSTRACT

Wood chip production from short-rotation coppice (SRC) can be an interesting opportunity for farmers and for the environment. SRC cultivation in fertile arable land, with full mechanisation of the operations, results in higher yields. However, the establishment of SRC is more rational in marginal areas where the conventional crops cannot provide suitable results. In this context, the mechanisation of SRC plays a relevant role, and the availability of small machinery is a key element.

In this study, two different willow SRC management regimes, characterised by the adoption of small mechanisation solutions for crop management and harvesting, were compared. The life cycle assessment (LCA) was applied considering 1 cubic metre of wood chips as the functional unit (FU) and a 'from cradle to gate' perspective regarding the system boundary. Primary data were directly collected via field trials and interviews with the farmers.

The results highlighted how the mechanisation of different field operations is the main cause of environmental impact, which is primarily due to the felling and chipping of stems. The 3-year SRC harvesting regime, despite lower productivity, presents better environmental performance compared to the 2-year one for all the evaluated impact categories, owing to a reduction of the environmental impact related to harvesting.

1. Introduction

Since the early 1970s, many countries have been developing new crops to increase the biomass resource base for the production of bioenergy (Wright, 2006). The practice of growing trees on short rotations to produce lignocellulosic feedstock for the pulp, board, and energy industries is known by a variety of names, including short-rotation forestry (SRF), energy forestry in Sweden, short-rotation intensive culture (SRIC) in North America, and short-rotation coppice (SRC) in Europe (Mitchell et al., 1999). SRC for the production of biomass is considered as one of the solutions to help meet the European objectives to increase the amount of renewable energy and has been recognised as the most energy-efficient carbon-conversion technology to decrease greenhouse gas (GHG) emissions (Styles and Jones, 2007; Joubert-van der Merwe et al., 2020).

While this commercial agricultural crop is grown for the production of biomass, the rapid and large-scale change from 'conventional' agricultural crops to SRC has positive and negative implications on a range of environmental issues (Dimitriou et al., 2009; Vazifeh et al., 2023). However, despite technology rapidly advancing to utilise woody perennials, several questions concerning the environmental impacts of biomass and biofuel production remain unanswered (Talagai et al., 2020). In this context, several studies have assessed biomass energy applications to determine GHG balance and overall carbon balance (Quinkenstein and Jochheim, 2016; Fuertes et al., 2023). In fact, to ensure that energy crops live up to their promise of being energy-efficient, low-carbon sources of energy, it is important to quantify the impact of these systems under different management regimes using accepted performance metrics (Caputo et al., 2013; Zoli et al., 2023).

To assess the energetic and environmental performances of agricultural processes, different methodologies have been proposed over the years (Ramos, 2019). Among them, the life cycle assessment (LCA) is, by far, the most used and commonly accepted for quantifying the potential

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environmental impact related to a product, process, or service (ISO, 2006). Although it was originally developed for the analysis of industrial processes, in the last few years, it has been used more frequently in the fields of agriculture (Noya et al., 2015; Nikkhah et al., 2017; Ruiz-Colmenero et al., 2024; Duca et al., 2024), forest management (Proto et al., 2917; Pierobon et al., 2015), and agro-energy systems (Gonzalez-Garcia and Bacenetti, 2019; Djomo et al., 2019; Quinn et al., 2020). In addition, for the analysis of energy performance, different indicators have been proposed, such as the energy return on energy invested (EROEI) (Barti et al., 2011; Rye and Jackson, 2018; Mancuso et al., 2024), the cumulative exergy demand (CExD) (Stougie et al., 2018; Nabavi-Pelesaraei et al., 2022), and the cumulative energy demand (CED) (Huijbregts et al., 2010). CED is used as a predictor for the environmental burden of commodity; this is widely applied for the analysis of agricultural processes (Bösch et al., 2007; Sajid et al., 2023).

The LCAs carried out for SRC in the last 25 years focus on GHG or energy balance (Bacenetti et al., 2012a; Manzone et al., 2009, 2015). Moreover, most of these studies (Gonzalez-Garcia et al., 2012b; Gabrielle et al., 2013; San Miguel et al., 2015; Rugani et al., 2015; Krzyzaniak et al., 2013; Heller et al., 2004; Peric et al., 2020) refer to poplar and/or willow SRC cultivated via fully mechanised field operations. Hence, there is a lack of information about the energy and environmental performance of SRC cultivated on small and dispersed plots using general-purpose, small-sized machines and tools.

In this context, this study aims at evaluating the energy and environmental performance of SRC of willow (*Salix* spp.) in Romania considering different harvest regimes. For this purpose, the LCA was applied to primary data collected during experimental trials; furthermore, owing to the contribution analysis, the processes mainly responsible for the environmental impact were identified, and two scenarios involving different harvesting cycles were compared.

2. Materials and methods

In this study, the LCA was applied, considering an attributional approach to model two willow cultivation practices. In attributional LCA, the inventory data are attributed to the functional unit (FU) of the product system in accordance with a normative rule, and the evaluation of the environmental burdens is directly linked to production.

2.1. Goal and scope definition

The goal of this study is to delve into the environmental performances of SRC of willow in Romania considering two possible crop rotations. In detail, the two compared scenarios differ in terms of cutting cycle; in the baseline scenario (BS, 2-year SRC), the crop is harvested every 2 years, while in the alternative scenario (AS, 3-year SRC), a longer cutting cycle (3 years) is considered. These scenarios were selected as being representative for small-scale willow cultivation in Romania and likely in other countries and were shaped by the amount of time elapsed between two successive harvests, which, given the equipment used to harvest and likely given the aim of the farmers to earn a steady revenue at shorter time intervals, is typically 2–3 years (Talagai et al., 2017).

Romania possesses relatively new experience with willow cultivation (e.g. Scriba et al., 2014), which is typically different from well-known, large-scale willow cultivation practices, mainly using flexible, multi-purpose equipment for establishment and harvesting (Talagai et al., 2017, 2020). In addition, willow is typically cultivated on small and dispersed plots (Talagai et al., 2020), which are often located on lands unsuited for other agricultural crops, making it difficult to invest in and use highly mechanised purpose-designed equipment.

The main research questions of this study are as follows.

- How much is the potential environmental impact of 1 cubic metre of wood chips from willow SRC? How extensively does the variation of the crop rotation affect this impact?
- What are the main contributors (i.e. inputs, outputs, and/or subprocesses) of the environmental impact for the different environmental effects?
- Can the impact of wood production be reduced?

The outcomes of this study will be useful for the following individuals.

- LCA practitioners involved in wood production by SRC;
- technicians' and farmers' associations, to design, following the results of the contribution analysis, a less impactful cultivation practice; and
- policymakers involved in the agricultural systems and in designing public subsidies (e.g. the Common Agricultural Policy program) to define policies more related to environmental performance (e.g. by modulating the subsidies according to the potential environmental impact of different cultivation practices).

The geographical scope of this study is Eastern Europe, in particular the central part of Romania, in an area about 600 m above sea level (45°53′24″N, 25°59′19″E).

2.2. Description of crop cultivation

Willow is grown following the schema of the SRC cultivation practice (Londo et al., 2005; Hauk et al., 2014), and during a 12-year-long crop cycle, different field operations are carried out. In further detail, the crop cycle is divided into different rotations; regarding the field operations, some are carried out only for planting or final removal of the plantation, while others are repeated during each rotation. To model its environmental impact, the willow SRC crop cycle was divided into different subsystems:

Subsystem A — Planting: This subsystem involves soil tillage, planting, and the cutback operation. Soil tillage foresees primary tillage (ploughing of 35 cm depth), followed by one or more rounds of harrowing. The latter is usually carried out using a rotary harrow; one intervention is usually enough in medium textured soil, but in clayey soils, more interventions may be required. Planting is partly mechanised (Talagai et al., 2020); this operation is performed using a planter coupled with a tractor, and 20 cm in length cuttings are placed vertically into the soil. A proper soil amendment is a key aspect to increase the effectiveness of planting and to reduce mortality as a result of dehydration of the cuttings. At the end of the first growing season, a cutback operation is performed using brush cutters to enhance sprouting. Regarding this subsystem, between the SRC, the main difference refers to the plantation layout and, consequently, to the number of cuttings (12,000 and 9000 cuttings/ha are used for 2-year SRC and 3-year SRC, respectively).

Subsystem B: Crop Management: This subsystem aims to assure a regular plant's growth. With the wood chip being destined for energy production, the quality of the wood is less important than in the plantation, where the biomass is used to produce plywood and/or other products with higher added value. For this reason, crop management is simple and involves only fertilisation and weed control. Fertilisation is carried out using a broadcaster spreader and applying mineral fertiliser (urea). This operation takes place once per crop rotation in the year of planting and in each year after harvesting in the 2-year SRC. In the 3-year SRC, fertilisation is carried out in the first two years of the crop cycle, and the applied dose is slightly lower because the plants' roots explore a wider volume of soil. Weed control involves herbicide application; no irrigation and pest and disease control measures are carried out.

Subsystem C: Harvesting and Transport: The harvesting operations are partially mechanised. Felling is carried out using brush cutters by two teams of two workers each. In each team, one worker operates a brush cutter, while the second one directs the stems during the felling. The brush cutters are equipped with a steel saw blade, having a mass of 8.7 kg, 2.1 kW power output, 46 cm^3 of cylinder displacement, and specific fuel consumption equal to 450 g/kWh. Next, chipping is carried out by a chipper coupled by a tractor that is fed manually with willow stems gathered from up to 20 m. The wood chips are loaded onto the farm trailer for transport to the storage point. More details about the partially mechanised harvesting operation can be found in the work of Talagai et al. (2017).

Subsystem D: Soil Restoring: This involves the chopping of plant stumps and is carried out using a forestry shredder.

2.3. Functional unit

According to ISO Standard 14040 (ISO, 2006), the potential environmental impact must be related to the function provided by the system or product under assessment. In each LCA study, one or more FUs should be selected as the reference unit. The FU choice is a key step of each LCA study to properly describe the environmental results and to allow fair comparison with previous studies. The FU should quantify the provided function considering its quantity, quality, and duration.

The main function of the evaluated production system is to provide woody biomass for energy purposes; in this regard, the amount of produced wood chips is the best FU. Previous LCA studies on SRC (Roedl, 2010; Fiala and Bacenetti, 2012a; Gonzalez-Garcia et al., 2013; Livingston et al., 2022) and wood products (Proto et al., 2017; Bernardi et al., 2018; Quinn et al., 2020) selected the product mass as the FU. However, the fresh mass is affected by the moisture content of the wood, while the volume is only slightly influenced by this parameter. For these reasons and considering that the main aim of the study is the comparison between two cultivation practices, three different FUs were considered.

- Volume-based FU: 1 cubic metre of willow wood chips
- Mass-based FU: 1 tonne of dry matter of willow wood chips
- Area-based FU: 1 ha of willow plantation

2.4. System boundary

The system boundary defines which unit processes are included in the product system as well as which inputs and outputs should be included (or excluded). The selection of which processes to include in the system depends on the goal of the study and the intended application of the results.

In this study, the system boundary was defined with a 'cradle to farm gate' perspective. Therefore, all the unit processes characterising the cultivation practices, from soil preparation to crop removal, were included. In further detail, the following activities were included: raw material extraction (e.g. metals, minerals, fuels), the manufacturing of different production factors (e.g. seedlings, fertilisers, pesticides, agricultural equipment, infrastructures), the use of inputs and related emissions (N and P compounds resulting from fertiliser application, diesel fuel emissions related to fuel combustion in the machinery engine and tire abrasion emissions), maintenance, and the final disposal of tractors, operative machines, and infrastructures.

Fig. 1 shows the system boundary for the two evaluated cultivation practices.

While ISO 14067 (ISO, 2018) states that soil organic carbon (SOC) changes resulting from land use and land use changes should be included in LCA studies, there is no consensus on how SOC should be modelled. For this reason, no change in the SOC content was considered. Moreover, in this study, the main factors affecting SOC (soil tillage, organic fertilisation, crop residue management, and crop cycle duration) are consistent; therefore, the impact on SOC changes on the environmental performances of the two SRCs would be similar.

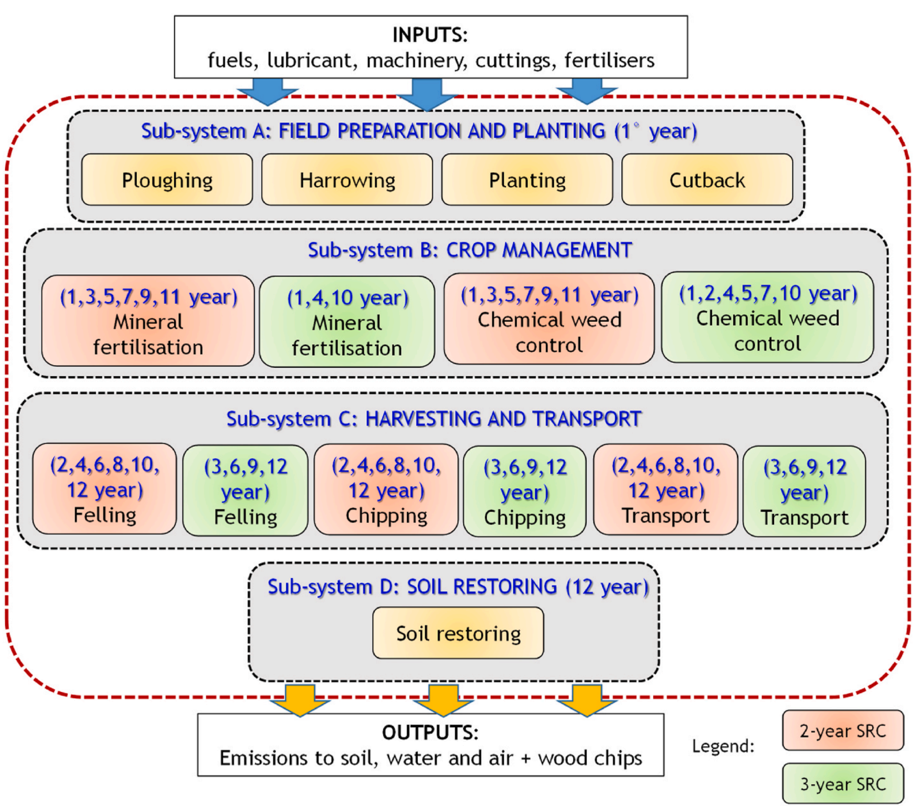

Fig. 1. System boundary for the two willow SRCs.

2.5. Inventory

Primary inventory data regarding the two crop cultivations were collected during field trials and by means of surveys at the farm and questionnaires with the farmer. In detail, the two trials – one for the BS and one for the AS – were carried out on neighbouring fields characterised by the same soil texture, slope, and orientation as well as by the same previous crop. In both scenarios, the cultivation period was the same, from 2012 to 2023. Furthermore, additional field trials were carried out to collect all the inventory data required to model the planting and harvesting operations.

The following data were directly collected.

- biomass productivity;
- the timing and number of repetitions of the different operations during the crop cycle;
- the size, mass, operative length and width, required power, age, annual average working time, and life span of each machine;
- the power, mass, exhaust gas emission stage, age, annual working time, and life span of each tractor; and
- the amount of production factors consumed (fuel, cuttings, fertilisers, etc.); for planting and harvesting, diesel fuel consumption was directly measured with the 'full-tank method' (Lovarelli et al., 2017).

The amount of machinery virtually consumed during each field operation was estimated according to the work of Lovarelli and Bacenetti (2017) as well as considering the annual working time and the physical and economic life span.

Table 1 summarises the main inventory data regarding crop cultivation.

Concerning the background data, information about the production of fuels, urea, tractors, and agricultural machines was retrieved from the Ecoinvent® Database (version 3.8).

The emissions related to fertiliser applications (nitrate leaching, ammonia volatilisation, and nitrous oxide from denitrification) were estimated through the IPCC (2019). In detail, direct emissions by the use of fertilisers considered the following default parameters: (i) N_2O to air: 0.041 kg N_2O/kg N synthetic fertiliser, (ii) NH_3 to air: 0.12 kg NH_3/kg N synthetic fertiliser applied, (iii) NO_3 to water: 1.33 kg NO_3/kg N synthetic fertiliser, and (iv) P to water: 0.05 kg P/kg P fertiliser applied.

With regard to emissions from pesticide applications, 100% of the active ingredients of the pesticides were considered as emitted into the soil (Environdec, 2019).

2.6. Life cycle impact assessment (LCIA)

During the third step of the LCA, the inventory results are characterised using the life cycle impact assessment (LCIA) method, and different environmental impact categories (environmental effects) are quantified. In this study, the results of the LCIA impact indicators are calculated for the recommended impact categories according to the EF 3.0 Method (adapted) V1.00 (Fazio et al., 2018), derived from the International Life Cycle Data System (ILCD) (ILCD, 2011). In detail, all 16 indicators recommended by the European Commission (EC) through the Product Environmental Footprint initiative (Zampori and Pant, 2019) were used.

- Climate change (CC; kg CO_2 eq)
- Ozone depletion (OD; kg CFC11 eq)
- Photochemical ozone formation (POF; kg NMVOC eq)
- Particulate matter (PM; disease inc.)
- Human toxicity, non-cancer (HT-noc; CTUh)
- Human toxicity, cancer (HT-c; CTUh)
- Acidification (AC; mol H+ eq)
- Eutrophication, freshwater (FE; kg P eq)
- Eutrophication, marine (ME; kg N eq)
- Eutrophication, terrestrial (TE; mol N eq)
- Ecotoxicity, freshwater (FEx; CTUe)
- Resource use, fossils (FRU; MJ)
- Resource use, minerals and metals (MMRU; g Sb eq)

The analysis was carried out using the Simapro software (version

Table 1
Main inventory data regarding the two SRCs (BS and AS).

Subsystem	Operation	Machine	Year of Execution		Tractor		Fuel Consumption	Production Factors		WT[b]
			2-y[a]	3-y[a]	kW	kg		Product	Amount (· ha^{-1})	h • ha^{-1}
A — Field Preparation and Planting	Ploughing	Plough	1	1	135	7600	27.7 kg ha^{-1}			1.1
	Harrowing	Rotary harrow	1	1	90	5050	18.6 kg ha^{-1}			1.7
	Planting	Transplanter	1	1	90	5050	6.6 kg ha^{-1}	Cutting	12,000 cuttings[c] 9000 cuttings[d]	6.5
	Cutback	Cutback machine	1	1		3620	10.9 kg ha^{-1}			7.0
B — Crop Management	Mineral fertilisation	Fertiliser spreader	1, 3, 5, 7, 9, 11	1, 4, 7, 10	90	5050	3.1 kg ha^{-1}	N	350 kg urea per intervention 2100 kg urea[c] 472.5 kg urea per intervention 1890 kg urea[d]	0.3
	Chemical weed control	Sprayer	1, 3, 5, 7, 9, 11	1, 2, 4, 5, 7, 10	90	5050	3.3 kg ha^{-1}	Herbicide	0.5 l ha fusillade (a.s.[e] = 13.7%)	0.40
C — Harvesting and Transport	Felling	Brush cutter	2, 4, 6, 8, 10, 12	3, 6, 9, 12	2.1[f]	8.7[f]	8.6 kg ha^{-1} [c] 10.8 kg ha^{-1} [d]		1198.3 m^3 [c] 224.1 t of dry matter[c] 1138.6 m^3 [d] 233.4 t of dry matter[c]	9.1[c] 11.4[d]
	Chipping	Chipper			110	6200	0.72 kg m^{-3}			n/a
	Transport	Trailer			90	5050	15.1 kg ha^{-1}			n/a
D — Crop Removal	Soil restoring	Forestry shredder	12	12	110	6200	40 kg ha^{-1}			8.00

Note: [a] 2-y = 2-year SRC (BS); 3-y = 3-year SRC (BS); [b] WT = working time; [c] = for 2-year SRC; [d] = for 3-year SRC; [e] a.s = active substance; [f] = for brush cutter; [g] = petrol two-stroke blend.

9.4.0.2).

Regarding the energy performance, the CED indicator was considered. CED is the amount of primary energy consumed during the life cycle of a product or service (Huijbregts et al., 2010; Frischknecht et al., 2015). Various CED impact assessment methods are used according to primary energy classification (Amor et al., 2010).

3. Results and discussion

3.1. Absolute environmental results

Table 2 reports the absolute results for the two scenarios considering 1 cubic metre of willow wood chips and 1 tonne of dry matter as willow wood chips as the FU, while the results considering 1 ha of willow plantation as the FU are reported in the supplementary material (Table S1). For all the evaluated impact categories, the AS (3-year SRC) shows lower environmental impact compared to the BS (2-year SRC) considering the three FUs. The impact reduction ranges from (i) 1.7%–6.5% when a volume-based FU is selected, (ii) 10.3%–14.7% considering the mass-based FU, and (iii) 6.6%–11.2% with the area-based FU. When the considered FU is 1 ha, the impact reduction between the BS and the AS is completely related to the different cultivation practices, being less intensive in the 3-year SRC (AS). In the case of 1 cubic metre of chips wood as the FU, an impact reduction is achieved despite the lower volume production (−4.98% with respect to the BS). From an environmental point of view, the volume yield reduction is more than offset by the reduced number of times that the SRC is harvested. When the considered FU is the dry matter, the differences between the BS and the AS become wider because the 3-year SCR shows higher dry matter yield (+4.16% with respect to the BS). In this case, the benefits of higher yield are summed up to the one linked to the less intensive cultivation practice.

The single score results are reported in the supplementary material (Table S2); compared to the BS, the AS shows a single score reduction of 13% (0.0207 pt for the AS vs 0.0239 pt for the BS). The contribution of the different impact categories is shown in Fig. 2. Among these categories, the major contributions are owed to acidification (about 25% in both scenarios), particulate matter (about 23% in both the scenarios), and marine (16% in the BS and 15% in the AS) and terrestrial eutrophication (about 21% in both scenarios).

3.2. Contribution analysis

Figs. 3 and 4 report the results of the contribution analysis. The different operations are grouped along with the one related to the consumption of fertilisers and pesticides.

For both scenarios, the following apply.

- Mechanisation is the main contributor to the environmental load of ozone depletion, photochemical ozone formation, and human toxicity and plays a relevant role (>30%) in climate change, freshwater eutrophication and ecotoxicity, and resource use (both fossils and minerals and metals). In detail, this impact is due to
  - o *fuel consumption* for ozone depletion and fossil resource use,
  - o *the emission of pollutants* via the exhaust gases as a result of fuel combustion in the internal combustion engines of tractors and machines for the climate change (i.e. carbon dioxide), photochemical ozone formation (i.e. nitrous oxides and NMVOC), and human toxicity–related impact categories (i.e. carbon monoxide),
  - o the manufacturing of different machines for freshwater eutrophication and mineral and metal resource use,
- Ammonia emissions related to fertilising for particulate matter formation, acidification, and terrestrial eutrophication,
- Nitrate emission for marine eutrophication, and
- Mineral fertiliser manufacturing for resource use (both fossils and minerals and metals).

For the other contributors, the emission of dinitrogen monoxide is responsible for about 35%–40% of climate change, but the role of cutting production and pesticide emission is small (always lower than 5%, except for freshwater eutrophication). The reduced impact caused by the emission of active pesticide ingredients into the environment is strictly related to the application in small amounts.

3.3. Impact of felling with a motor-manual solution

Regarding the operation of stem felling, carried out with the brush cutter, the absolute environmental performances for 1 h of operation are reported in Table 3. Fuel consumption is the main contributor for 4 of the 13 evaluated impact categories (ozone depletion, 99%; particulate matter, 58%; freshwater ecotoxicity, 70%; resource fossil use, 98%), the emission caused by fuel combustion for 6 (ozone depletion, 99%; photochemical ozone formation, 85; human toxicity, non-cancer, 81%; acidification, 70%; eutrophication, marine, 90%; eutrophication, terrestrial, 90%), and the manufacturing, maintenance, and disposal of brush cutters for 3 (human toxicity, cancer, 82%; eutrophication, freshwater, 51%; mineral and metal resource use, 81%).

3.4. Cumulative energy demand (CED) results

Table 4 reports the comparison between the two scenarios in terms of CED results; the AS shows better performance compared to the BS, with a reduction of CED ranging from 2.9% to 4.7%. With regard to the contribution analysis, the results are shown in the supplementary material (Figs. S1 and S2). For both scenarios, harvesting operations and fertiliser consumption are the two main hotspots, with an aggregated

Table 2
Absolute environmental impact for the two scenarios (Δ = impact variation) considering the two selected FUs (1 cubic metre of wood chips, 1 tonne of wood chips – dry matter).

Impact Category	Unit	FU = 1 cubic metre			FU = 1 tonne of dry matter		
		BS 2-year	AS 3-year	Δ	BS 2-year	AS 3-year	Δ
Climate change	kg CO_2 eq	10.543	10.120	−4.0%	56.378	49.368	−12.4%
Ozone depletion	mg CFC11 eq	1.252	1.217	−2.8%	6.696	5.938	−11.3%
Photochemical ozone formation	g NMVOC eq	48.155	47.328	−1.7%	257.514	230.870	−10.3%
Particulate matter	disease inc.	6.88×10^{-06}	6.53×10^{-06}	−5.1%	3.7×10^{-05}	3.2×10^{-05}	−13.4%
Human toxicity, non-cancer	CTUh	9.15×10^{-08}	8.91×10^{-08}	−2.7%	4.9×10^{-07}	4.3×10^{-07}	−11.2%
Human toxicity, cancer	CTUh	3.11×10^{-09}	3.00×10^{-09}	−3.6%	1.7×10^{-08}	1.5×10^{-08}	−12.0%
Acidification	mol H+ eq	1.009	0.958	−5.0%	5.394	4.674	−13.4%
Eutrophication, freshwater	g P eq	0.755	0.706	−6.5%	4.037	3.442	−14.7%
Eutrophication, marine	kg N eq	0.475	0.449	−5.4%	2.542	2.192	−13.7%
Eutrophication, terrestrial	mol N eq	4.477	4.253	−5.0%	23.943	20.748	−13.3%
Ecotoxicity, freshwater	CTUe	124.709	119.222	−4.4%	666.891	581.573	−12.8%
Resource use, fossils	MJ	109.207	105.552	−3.3%	583.996	514.890	−11.8%
Resource use, minerals and metals	g Sb eq	0.056	0.053	−4.0%	0.298	0.261	−12.4%

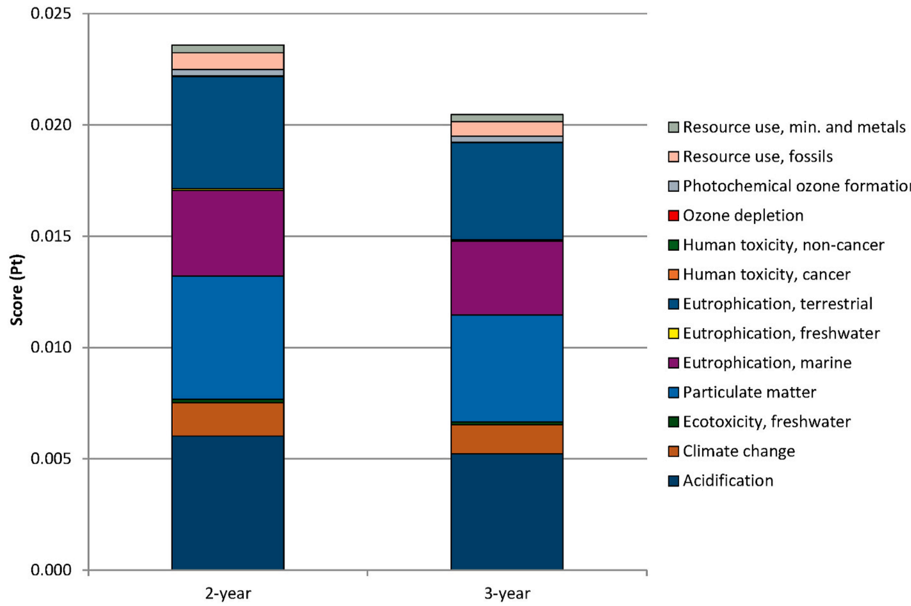

Fig. 2. Single score results: Contribution analysis for the two scenarios.

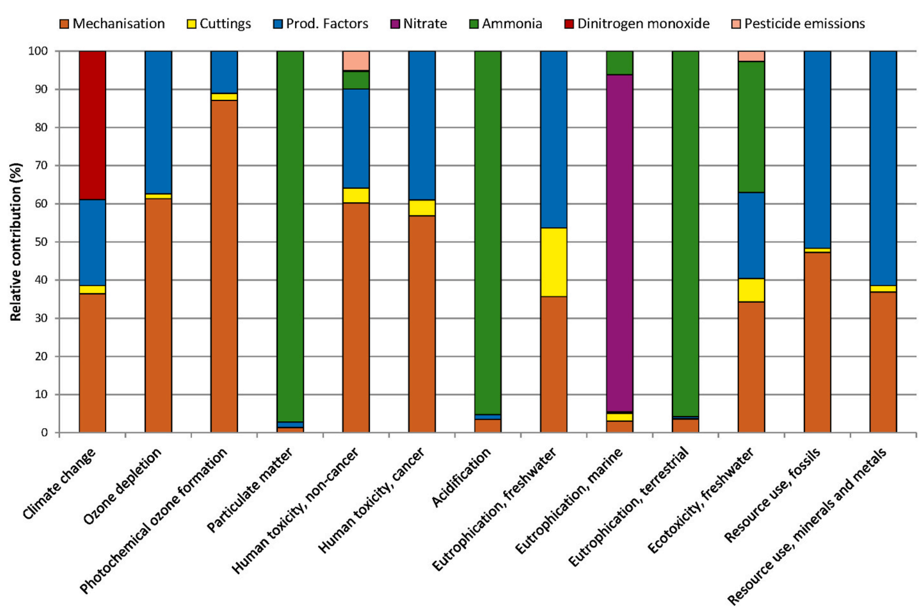

Fig. 3. Contribution analysis for the 2-year willow SRC.

contribution ranging from 70.9% to 91.5% in the BS and from 71.3% to 91.6% in the AS. Among the different harvesting operations (felling, chipping, and biomass transport), chipping is the main contributor, with a share of the CED ranging from 15.7% to 48.7% in the BS and from 16.2% to 50.2% in the AS.

3.5. Sensitivity and uncertainty analyses

To test the robustness of the achieved environmental results, sensitivity and uncertainty analyses were carried out.

3.5.1. Sensitivity analysis

A sensitivity analysis was performed to investigate the effect of key parameters, assumptions, and methodological choices of the study. Thus, the following aspects were considered.

- Biomass yield: While the cultivation practice of SRC is well-known and quite standardised, its productivity can be variable because of pest and disease attacks and/or drought, in particular during the planting year or in the years after harvesting. As such, for willow SRC, productivities ranging from 75 to 202 tonnes of dry matter per hectare were observed during a 12-year crop cycle (Goglio and Owende, 2009; Rosso et al., 2013; Gonzalez-Garcia et al., 2013; Bacenetti et al., 2016), while a yield variation of ±20% was considered in both scenarios.
- Mortality: In this regard, an average mortality of 5% was considered for both scenarios. However, a longer cutting cycle reduces the stem's mortality and, consequently, increases the biomass produced during the whole crop cycle. This additional biomass production is concentrated in the final part of the crop cycle (where the negative effects of mortality on productivity are higher). In the alternative

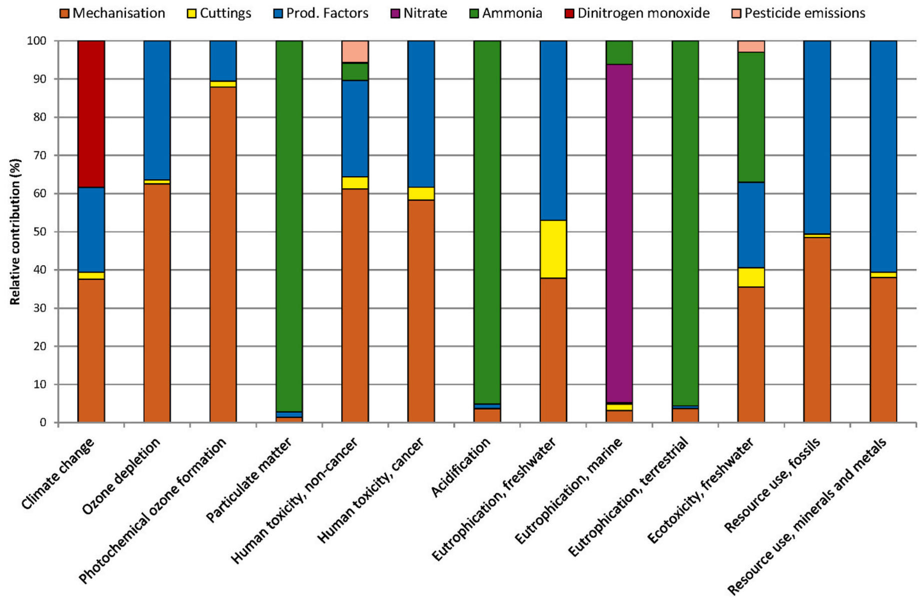

Fig. 4. Contribution analysis for the 3-year willow SRC.

Table 3
Absolute environmental impact for 1 h of operation of the brush cutter during felling.

Impact Category	Unit	Fuel	Brush Cutter	Emission from Fuel Combustion	Total
Climate change	kg CO_2 eq	0.461	0.102	3.068	3.631
Ozone depletion	mg CFC11 eq	0.789	0.005	0.000	0.795
Photochemical ozone formation	g NMVOC eq	3.145	0.430	20.390	23.965
Particulate matter	disease inc.	3.02×10^{-08}	9.31×10^{-09}	1.23×10^{-08}	5.18×10^{-08}
Human toxicity, non-cancer	CTUh	5.60×10^{-09}	2.53×10^{-09}	3.61×10^{-08}	4.42×10^{-08}
Human toxicity, cancer	CTUh	1.89×10^{-10}	1.81×10^{-09}	2.06×10^{-10}	2.21×10^{-09}
Acidification	mol H+ eq	0.006	0.001	0.016	0.023
Eutrophication, freshwater	mg P eq	36.385	38.743	0.000	75.127
Eutrophication, marine	g N eq	0.699	0.130	7.126	7.956
Eutrophication, terrestrial	mol N eq	0.008	0.002	0.078	0.088
Ecotoxicity, freshwater	CTUe	25.195	8.587	0.231	34.013
Resource use, fossils	MJ	47.567	1.190	0.000	48.757
Resource use, minerals and metals	mg Sb eq	0.624	2.741	0.000	3.365

scenario, a reduction of mortality to 3% was considered with an increase of the yield up to 2%.

The results of the sensitivity analysis are reported in Table S2. Yield variation deeply affects all the impact categories. In detail, in the case of 20% yield reduction, the 3-year SRC shows higher impact compared to the 2-year SRC with no yield variation. As expected, the impact on environmental performance is greater than the yield variation itself.

In the AS, a reduction of stump mortality is considered if the

Table 4
CED: Comparison between the two scenarios.

Category	Unit	1 ton cubic meter		1 ton dry matter	
		BS 2-year	AS 3-year	BS 2-year	AS 3-year
Non-renewable, fossil	MJ	115.680	111.788	618.607	545.306
Non-renewable, nuclear	MJ	2.479	2.373	13.254	11.577
Non-renewable, biomass	MJ	0.0022	0.0021	0.0118	0.0105
Renewable, biomass	MJ	0.996	0.954	5.327	4.655
Renewable, wind, solar, geotherm.	MJ	0.355	0.339	1.900	1.652
Renewable, water	MJ	0.955	0.917	5.107	4.475

environmental impact is reduced from 0.50% to 1.94%. Though small, this impact reduction is achieved for all the environmental effects and without any modification of the cultivation practice.

Concerning the comparison between the two scenarios, different LCIA methods were used to characterise the inventory. In detail, apart from the EF 3.0 method, the ReCiPe 2016 Midpoint (H) method (version 1.04/World) (Goedkoop et al., 2013; Huijbregts et al., 2017) was considered.

The environmental results for the two scenarios (BS and AS), calculated using a different LCIA method, are shown in Table 5. A direct comparison between the environmental results calculated using the two LCIA methods cannot be drawn for all the environmental effects. In fact, different impact categories and different units of measure are used. Despite this, the comparison shows similar results irrespective of the selected LCIA method. In more detail, the two LCIA methods provide univocal results for the identification of the best/worst scenario.

3.5.2. *Uncertainty analysis*

An uncertainty analysis was run on the BS and AS using the Monte Carlo technique (1000 iterations and a confidence interval of 95%) to test the robustness of the results. Uncertainty analysis was carried out on the background system based on the uncertainty values reported in the databases and considering a lognormal distribution, and the results are reported in Fig. 5. The bars on the left represent the probability that the environmental impact of the AS is lower than that of the BS, while the bars on the right mean the opposite (i.e. the environmental impact of

Table 5
Absolute and relative results for the two scenarios with the recipe LCIA method.

Impact Category	1 cubic meter		1 t of dry matter	
	BS 2-year	AS 3-year	BS 2-year	AS 3-year
Global warming	10.502	10.082	56.163	49.178
Stratospheric ozone depletion	0.156	0.147	0.833	0.719
Ozone formation, human health	41.878	41.209	835.511	732.426
Fine particulate matter formation	89.663	85.482	223.946	201.019
Ozone formation, terrestrial ecosystems	42.475	41.792	479.481	416.984
Terrestrial acidification	0.651	0.619	227.138	203.862
Freshwater eutrophication	1.719	1.576	3.483	3.017
Marine eutrophication	0.128	0.121	9.192	7.688
Terrestrial ecotoxicity	20.729	19.993	0.683	0.588
Freshwater ecotoxicity	0.196	0.189	110.848	97.528
Marine ecotoxicity	0.250	0.240	1.050	0.922
Human carcinogenic toxicity	0.282	0.272	1.339	1.169
Human non-carcinogenic toxicity	6.610	6.380	1.509	1.328
Mineral resource scarcity	1.746	1.402	35.346	31.124
Fossil resource scarcity	0.022	0.021	9.339	6.837

willow production in the AS is higher than that in the BS).

The uncertainty analysis results show that the modelling of the environmental impact of SRC is robust; the environmental outcomes are trustworthy for all the evaluated impact categories except for the human toxicity–related impact categories. For 12 of the 13 impact categories, the BS has a higher impact than the AS with a level of statistical significance higher than 99%. The level of statistical significance is lower than 70% only for HT-noc (BS > AS, with a level of statistical significance of 57%) and HT-c (AS > BS, with a level of statistical significance of 66%). The uncertainty caused by the selection of the data source, model imprecision, and variability of data does not significantly affect the environmental results.

3.6. Comparison with previous studies

A direct comparison among the results of this study and previously carried out LCAs of SRC of willow is made difficult by several methodological choices (e.g., use of different functional unit and system boundary, selection of diverse LCIA methods and/or different impact categories) as well as by the different assumptions and/or modelling choices (e.g., regarding the estimation of the emissions from fertilizer and pesticide applications). In any case, if the comparison is limited to LCA studies selecting a mass-based FU and carried out with a "from cradle to gate farm" perspective and to a limited number of impact categories, the comparison among different studies can be drawn and can be useful to better appreciate if the cultivation in marginal areas as well as the adoption of small-mechanisation positively affect the sustainability of willow SRC.

The results regarding the impact on climate change of this study (56 kg CO_2 eq./t and 49 kg CO_2 eq./t, for 2-years and 3-years willow SRC, respectively) are slightly higher than the ones found by.

- Bacenetti et al. (2016) 33.66 and 24.69 kg CO_2 eq./t for the most productive willow clone and for the willow on average, respectively,
- San Miguel et al. (2015) 43.11 kg CO_2 eq./t for poplar,
- Gonzalez-Garcia et al. (2012) (35.46 kg CO_2 eq./t for poplar),
- Roedl (2010) (38.4 kg CO_2 eq./t for poplar),
- J. Bacenetti et al. (2012) (33.59 CO_2 eq./t for poplar),
- Gonzalez-Garcia et al. (2013) 26.44 CO_2 eq./t for willow),

but are lower respect to Rugani et al. (2015) (66.94 kg CO_2 eq/t for mixed-woody-crop willows clones and local species).

The different productive yields are the main reason explaining the difference about the Climate Change results in the different studies. Even if in all the studies the mechanisation of the field operations plays a non-negligible role in the CC results, the production yield is the main driver of the environmental results. In this regard, it should be considered that the low-medium productive yield recorded for willow SRC in marginal areas in Romania negatively affects the environmental performances.

4. Conclusions

The production of wood chips from SRC as biofuel for renewable energy production is an effective way to diversify farmer revenue, to reduce monoculture and intensive crop cultivations, and to decrease the use of fossil fuels while reducing the environmental pressure of agricultural areas. However, the establishment of SRC plantation is usually more suitable for marginal areas. For SRC, while the production yields are higher in fertile arable soil, in this context, the main crops (e.g. cereals and oil crops) provide better economic results. Consequently, marginal areas represent one of the most rational locations for SRC; in this situation, the main crops do not provide noteworthy results because the production cost related to their intensive cultivation practice can

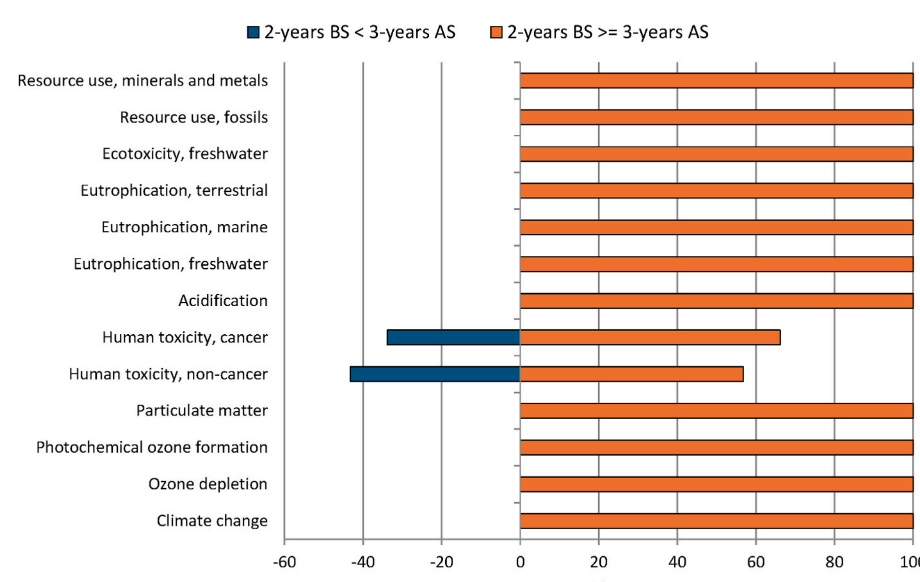

Fig. 5. Results of the uncertainty analysis.

hardly be repaid by the revenue. On the contrary, SRCs, with their simplified and less intensive cultivation practice, can be an effective solution; in this context, mechanisation plays a relevant role. In further detail, considering that the fields in marginal areas are usually dispersed throughout the territory and characterised by small size, the availability of small mechanisation solutions is a key element.

In this study, two different willow SRCs, characterised by the adoption of flexible mechanisation solutions for crop management and harvesting, were compared. The results highlighted how the mechanisation of different operations is the main contributor to the environmental impact, with harvesting operations (felling carried out with a brush cutter, chipping, and transport) holding, by far, the main share of the total impact. For this reason, the 3-year SRC, despite a lower yield, presents better environmental performance owing to a reduction of the environmental impact related to harvesting.

CRediT authorship contribution statement

Stelian Alexandru Borz: Writing – review & editing, Project administration, Conceptualization. **Salvatore Papandrea:** Investigation, Data curation. **Michele Zoli:** Software, Data curation. **Jacopo Bacenetti:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Andrea Rosario Proto:** Writing – review & editing, Supervision, Investigation, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2024.100249.

Data availability

Data will be made available on request.

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