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Life cycle assessment of bioenergy production from short-rotation coppice plantation in Hungary

Budi Mulyana[1]*, *Andrea Vityi*[2], *András Polgár*[2]

[1]*Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta, Indonesia*
[2]*Faculty of Forestry, University of Sopron, Sopron, Hungary*

**Corresponding author: budimulyana@ugm.ac.id*

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Abstract: A short-rotation coppice (SRC) system for bioenergy production is vital to supporting climate change mitigation by absorbing CO_2 from the atmosphere and storing carbon as biomass. However, SRC's operation also released some greenhouse gas emissions, affecting the environment. This study aims to assess the potential environmental impacts through the life cycle assessment method in bioenergy production from the SRC system. Data was collected through a literature review and database, and the impact categories were then analysed using Sphera LCA for Experts Education License software (Version 9.2.1.68, 2020). In managing plantations for bioenergy production, plants during one rotation (15 years) will be harvested every 3 years (harvesting cycle). Then, there will be five harvesting cycles during a single rotation. The result showed that the first cycle had the highest environmental impacts because the inputs (fuel, lubricant, electricity, fertiliser, and pesticides) in this cycle were higher than others. The highest contribution comes from the first and end cycles as 3 200 and 2 700 kg CO_2 eq, respectively. Meanwhile, cycles 2, 3, and 4 contribute to the carbon footprint as 2 500 kg CO_2 eq for each cycle. Based on input, fuel consumption has resulted in higher environmental impacts than lubricants, fertilisers, and electricity consumption. In conclusion, energy consumption (fuel, lubricant, and electricity) and agrochemicals (fertilisers and pesticides) have released emissions and affected the environment. In the future, fuel and agrochemical consumption should be reduced to minimise the negative environmental impacts in the short-rotation coppice system.

Keywords: carbon footprint; climate change mitigation; environmental impacts; fast-growing species; forest plantation

The issue of environmental impacts has emerged as a prominent area of concern in the broader discourse on climate change mitigation. The adoption of eco-friendly production methodologies is predicated on the principle of minimising greenhouse gas emissions, a strategy that seeks to mitigate the environmental ramifications of human activity. Life cycle assessment (LCA) is a method of assessing the environmental impacts associated with the production processes of products or services, with the aim of protecting the environment (ISO 14040 and ISO 14044). LCA provides scientific evidence of a product's sustainability and environmental performance (Sahoo et al. 2019).

The standardisation of LCA was initiated in 2006 with the establishment of ISO 14040, Environmental Management – Life Cycle Assessment – Principles and Framework, and ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines. However, the application of LCA in forestry did not become widespread until the end of the 2010s (Klein et al. 2015). A research article published in Scopus and Web of Science further substantiates this claim, asserting that LCA research

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in Hungary's forestry industries commenced in the early 2010s (Mulyana et al. 2023). Environmental assessment using LCA has been applied in the forest operation of short-rotation energy plantations (Polgár et al. 2018, 2019) and wood utilisation (Király et al. 2022; Polgár 2023).

The development of bioenergy plantations has emerged as a promising solution in the context of energy transition. Bioenergy plantations provide biomass for energy, thereby contributing to the achievement of a carbon neutrality scheme. Biomass for energy can be categorised into three distinct groups: woody biomass, herbaceous biomass, and fruit biomass (Miranda et al. 2015). In addition, Miranda et al. (2015) have delineated that the classification of woody biomass encompasses forest waste, remnants from the wood industry, and woody cultivation. The biomass utilised in this study is derived from woody cultivation managed with a short-rotation coppice (SRC) system. The present study aligns with the findings of Mulyana et al. (2024), who examined SRC plantations (poplar and black locust), emphasising their role in providing environmental services and their capacity to absorb carbon.

The SRC system has been extensively utilised for bioenergy production, particularly in the Northern Hemisphere. Examples of SRC bioenergy production include its application in China (Wang et al. 2023), the Czech Republic (Štochlová et al. 2019), Germany (Langhof, Schmiedgen 2023), Italy (Bacenetti et al. 2016a; Manzone, Calvo 2016), Poland (Krzyżaniak et al. 2023), Spain (Fernández et al. 2020), and the United States of America (Eisenbies et al. 2017; Morales-Vera et al. 2022) The management practices of SRC systems for bioenergy production also varied, depending on the site characteristics.

Characteristics of SRC can be seen from the species, cutting cycle, rotation, harvesting methods, and stand density. The main purpose of SRC is to provide bioenergy (fuelwood and biofuel) (Hart et al. 2015; Pereira, Costa 2017). The common species that have been cultivated in SRC plantations are poplar, black locust, eucalyptus, and willow (Bergante et al. 2016; Ferreira et al. 2017; Oliveira et al. 2018). The cutting cycles in SRC systems are varied, from 2 years to 8 years (Fernández et al. 2020; Rodrigues et al. 2021; Schiberna et al. 2021; Johnston et al. 2022; Stolarski, Stachowicz 2023). Furthermore, the rotations for SRC are 15, 20, and 25 years (Rodrigues et al. 2021; Schiberna et al. 2021). The harvesting methods that are employed in SRC plantation are single pass cut-and-chip harvester, double pass cut-and-store harvester, cut-and-bale harvester, and cut-and-billet harvester (Vanbeveren et al. 2017; Eisenbies et al. 2021). For the stand density, one ha of SRC can comprise the planting of about 5 000–22 222 trees (González-García et al. 2012a, b; Schiberna et al. 2021; Livingstone et al. 2022).

However, the development of bioenergy plantations has also been linked to potential emissions, including carbon dioxide (CO_2), nitrogen dioxide (NO_2), methane (CH_4), and sulphur dioxide (SO_2), which are released through the consumption of fuel and agrochemicals, such as fertiliser and pesticides. In this study, the CML 2001 method was used for calculating the life cycle impact assessment, in accordance with that used by González-Garcia et al. (2012a, b) and Livingstone et al. (2022) in short-rotation coppice systems in Italy, Sweden, and Northern Ireland. For example, timber production on poplar plantations in Italy has been associated with acidification and eutrophication resulting from fertiliser application (Lovarelli et al. 2018). Furthermore, the production of seedlings for softwood and hardwood has been linked to potential impacts such as aquatic ecotoxicity, global warming potential, and human toxicity (Yousaf et al. 2024). The utilisation of machinery in forestry operations has been associated with elevated CO_2 emissions (Prinz et al. 2018; Spinelli, Moura 2019; De Francesco et al. 2022; Spinelli et al. 2022). The employment of LCA in forestry operations is imperative to assess the environmental ramifications and offer alternative solutions.

This study aims to assess the potential environmental impacts on bioenergy production in short-rotation coppice systems, focusing on the environmental impacts based on activities (cutting cycles) and inputs (fuel, lubricant, electricity, and fertiliser).

MATERIAL AND METHODS

The methodology employed in this study to evaluate the environmental impacts of bioenergy production in short-rotation coppice systems was guided by the principles and framework outlined in ISO 14040, 'Environmental management – life cycle assessment – principles and framework' and the requirements and guidelines stipulated

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in ISO 14044 'Environmental management – life cycle assessment – requirements and guidelines'.

Data for life cycle inventory was collected from a literature review and LCA's software database. Fuel and lubricants, fertilisers, and pesticide consumption were required as input data during the rotation. The most significant obstacle in the LCA process is the availability of inventory data, which practitioners and researchers address by employing proxy data (Kouchaki-Penchah et al. 2016). Furthermore, Kouchaki-Penchah et al. (2016) explained that the proxy data may be collected from literature, such as the LCA analytical software database (Ecoinvent and ETH-ESU 96 database), reports, and peer-reviewed papers.

Literature and databases can provide information on fuel consumption for machinery and agrochemicals (fertilisers and pesticides) (Oneil, Puettmann 2017; Zhang et al. 2020). However, due to limitations in the available data, we employ the equation developed by Cantamessa et al. (2022) to estimate fuel consumption (see Equation 1 below). Cantamessa et al. (2022) developed an alternative estimation method that utilises projections from multiple data sources, a strategy that has been employed in studies focusing on the Northwest United States (Oneil, Puettmann 2017) and China (Zhang et al. 2020).

$$F = Sc \times P \times d \times t \quad (1)$$

where:

F – fuel consumption ($kg \cdot ha^{-1}$);

Sc – specific fuel consumption (fixed to 0.25 $kg \cdot kWh^{-1}$);

P – maximum engine power (kW);

d – power utilisation (%);

t – time (h).

Furthermore, the life cycle impact assessment was conducted using Sphera LCA for Experts Education License software (Version 9.2.1.68, 2020). Sphera LCA for Experts Education License is a software that calculates environmental impacts using methods such as CML 2001, Environmental Footprint (EF) 3.0, IPCC AR5, ReCIPe 2016, and TRACI.

Goal and scope definition. According to Hungarian Law, Act LIV of 1996 on Forests and the Protection of Forests, planting a row of trees, a tree group, and wooded pastures is classified as tree plantations. In this study, the black locust and poplar plantation for bioenergy production with short-rotation coppice systems was categorised as tree plantations. The operation of tree plantations presents a series of challenges, including on-site activities such as site preparation, silvicultural operations, infrastructure development, transportation, and off-site activities, including product manufacturing and distribution. In this research, we had to define the goal and scope. Furthermore, a system boundary has been delineated to emphasise the tree plantation processes, from planting to harvesting. The research aims to systematically assess the environmental impact of short-rotation coppice system plantations for bioenergy production in Hungary.

It is acknowledged that the system boundaries in forest operations vary across studies or research on LCA for forestry operations. Research on LCA with the system boundaries cradle-to-grave approach encompasses all activities from site preparation to the end of wood products disposal (Schweier et al. 2019). The cradle-to-farm gate system boundaries delineate the scope of activities, including site preparation, silvicultural operations, and final harvesting (Lovarelli et al. 2018). Because this research focused on on-site tree plantation operations, we adopted the cradle-to-farm gate system boundary (Figure 1). Furthermore, the cradle-to-gate system boundary for bioenergy production has been applied in poplar biomass production (Cantamessa et al. 2022; Krzyżaniak et al. 2023), biodiesel production from oil palm and physic nut in Indonesia (Siregar et al. 2015), and biochar production from forest residues (Puettmann et al. 2020).

In this study, we adopted a methodological approach consistent with that employed by Mulyana et al. (2024) in their examination of SRC plantation management in Hungary. The system boundary was initiated with the site preparation, plantation establishment, and growth maintenance through the application of fertiliser and pesticides during the first year. In the subsequent year, the focus shifted to the maintenance of growth. In the third year, the bioenergy plantation will be harvested, and it will naturally sprout and grow until the next harvest. Following the final harvest in the 15th year, the plantation will be liquidated and then replanted with new seedlings. In summary, the activities involved in short-rotation forestry include site preparation, site ending, silvicultural operations, secondary/off-site processing, transport, and chipping (Klein et al. 2015).

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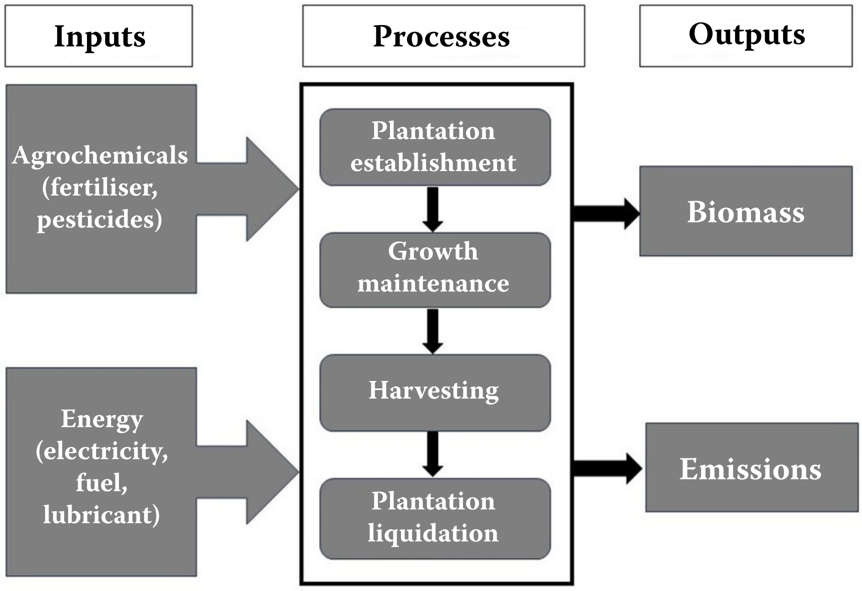

Figure 1. System boundary of bioenergy production in short-rotation coppice systems

Functional unit. The decision to choose a functional unit is an important step in the life cycle assessment process since it involves assessing input and output. According to Martínez-Blanco et al. (2015), the functional unit serves as the primary unit of analysis in LCA. In this study, the functional unit was a one-hectare short-rotation coppice system for bioenergy production. We follow Bacenetti et al. (2014, 2016b) and Cantamessa et al. (2022), who employed the functional unit of area (1 ha) to evaluate the LCA of agricultural production systems. Furthermore, Polgár et al. (2018) also used the functional unit of 1 ha to estimate the carbon footprint of several harvesting work methods in short-rotation energy plantations in Hungary.

Life cycle inventory. According to ISO 14044, inventory analysis was performed to acquire qualitative and quantitative data for application within the system boundaries. The data may be measured, calculated, and approximated to determine the inputs and outputs of processes. The life cycle inventory phase is notably time-consuming, as its primary activity involves the aggregation and configuration of data for all operations within product systems, employing a range of techniques (Bjørn et al. 2018). The quality of life cycle inventory data is critical, as it has been demonstrated to have a significant impact on the outcomes of the LCA process (Siregar et al. 2015).

In this research, forest activities employed machinery to facilitate forest operations and agrochemicals to stimulate growth. Consequently, the primary inputs encompass fuel, lubricants to operate the machinery, and agrochemicals (fertilisers and pesticides) (Table 1). Input data in plantation management include seedlings, agricultural chemicals (fertilisers and insecticides) applied during stand growth, as well as fuel and lubricant for maintenance and harvesting operations (Oneil, Puettmann 2017; Zhang et al. 2020). In the context of plantation establishment, encompassing soil preparation, planting, and weed control, the fuel and lubricant consumption was recorded at 58.25 $L{\cdot}ha^{-1}$ and 1.98 $L{\cdot}ha^{-1}$, respectively (Barbara 2018). Furthermore, Barbara (2018) describes that the application of pesticide for weed control was 2.03 $L{\cdot}ha^{-1}$ and electricity consumption for seedling treatment was 1.5 Kw.

In the stand maintenance, the fuel, lubricant and fertiliser consumption were 35.2 $L{\cdot}ha^{-1}$, 1.584 $L{\cdot}ha^{-1}$, and 162 kg $N{\cdot}ha^{-1}$, respectively (Barbara 2018). Moreover, in the harvesting operations, the fuel and lubricant for tractors were 8.80 $L{\cdot}ha^{-1}$ and 0.396 $L{\cdot}ha^{-1}$. Furthermore, the fuel and lubricant consumption for harvester machines were 7.50 $L{\cdot}ha^{-1}$ and 0.135 $L{\cdot}ha^{-1}$ (Barbara 2018).

Life cycle impact assessment. Life cycle impact assessment (LCIA) is derived from the life cycle inventory analysis using software or manual calculation. According to the Directorate-General for Energy of the European Commission (DG Ener 2012), the equations used to estimate the

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Table 1. Inputs in forest operations for short-rotation coppice systems of black locust and poplar plantations

Inputs in forest operations	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Forest planting															
Fuel tractor	√														
Lubricant	√														
Fuel car	√														
Agrochemical	√														
Electricity	√														
Stand maintenance															
Fuel tractor		√		√	√		√	√		√	√		√	√	
Lubricant		√		√	√		√	√		√	√		√	√	
Fertiliser		√		√	√		√	√		√	√		√	√	
Coppicing/final harvesting															
Fuel tractor			√			√			√			√			√
Lubricant tractor			√			√			√			√			√
Fuel combine harvester			√			√			√			√			√
Lubricant combine harvester			√			√			√			√			√
Plantation liquidation															
Fuel tractor															√
Lubricant															√
Agrochemical															√

Source: Barbara (2018)

total emission of greenhouse gases in agricultural production are described by Equation (2):

$$e_{ec} = e_{fert} + e_{seeds} + e_{N_2O} + e_{fuel} \quad (2)$$

where:

e_{ec} – total greenhouse gas emissions;

e_{fert} – emissions from fertiliser application;

e_{seeds} – emissions from seeds;

e_{N_2O} – direct and indirect N_2O emissions according to IPCC 2006 guideline (IPCC 2006);

e_{fuel} – emissions from fossil fuel consumption.

In this study, the Sphera LCA for Experts Education License software was used for the LCIA calculation. The Sphera LCA for Experts Education License database modelling has been used widely by academia and researchers, practitioners, and policymakers to analyse the life cycle assessment of product processes (Kupfer et al. 2021). The Sphera LCA for Experts Education License software has been applied to analyse the LCIA for sustainability assessment of wood utilisation in Hungary (Polgár 2023), lignin nanoparticle biorefinery (Koch et al. 2023), and crop production in different harvesting systems in short-rotation energy plantation (Polgár et al. 2018, 2019). In Sphera LCA for Experts Education License software, the system boundary and life cycle data inventory are vital in developing a plan or framework for products' processes (Figure 2).

RESULTS AND DISCUSSION

Environmental impacts potential in short-rotation coppice for bioenergy production. The generation of bioenergy from short-rotation coppice systems has had ramifications for the environment, owing to the consumption of energy (fuel, lubricant, and electricity) and agrochemicals (fertiliser and pesticides) during the plantation management process. According to the CML 2001 method for life cycle impact assessment, the most significant impact was identified as marine aquatic ecotoxicity, followed by global warming potential and terrestrial ecotoxicity (Table 2). Consistent

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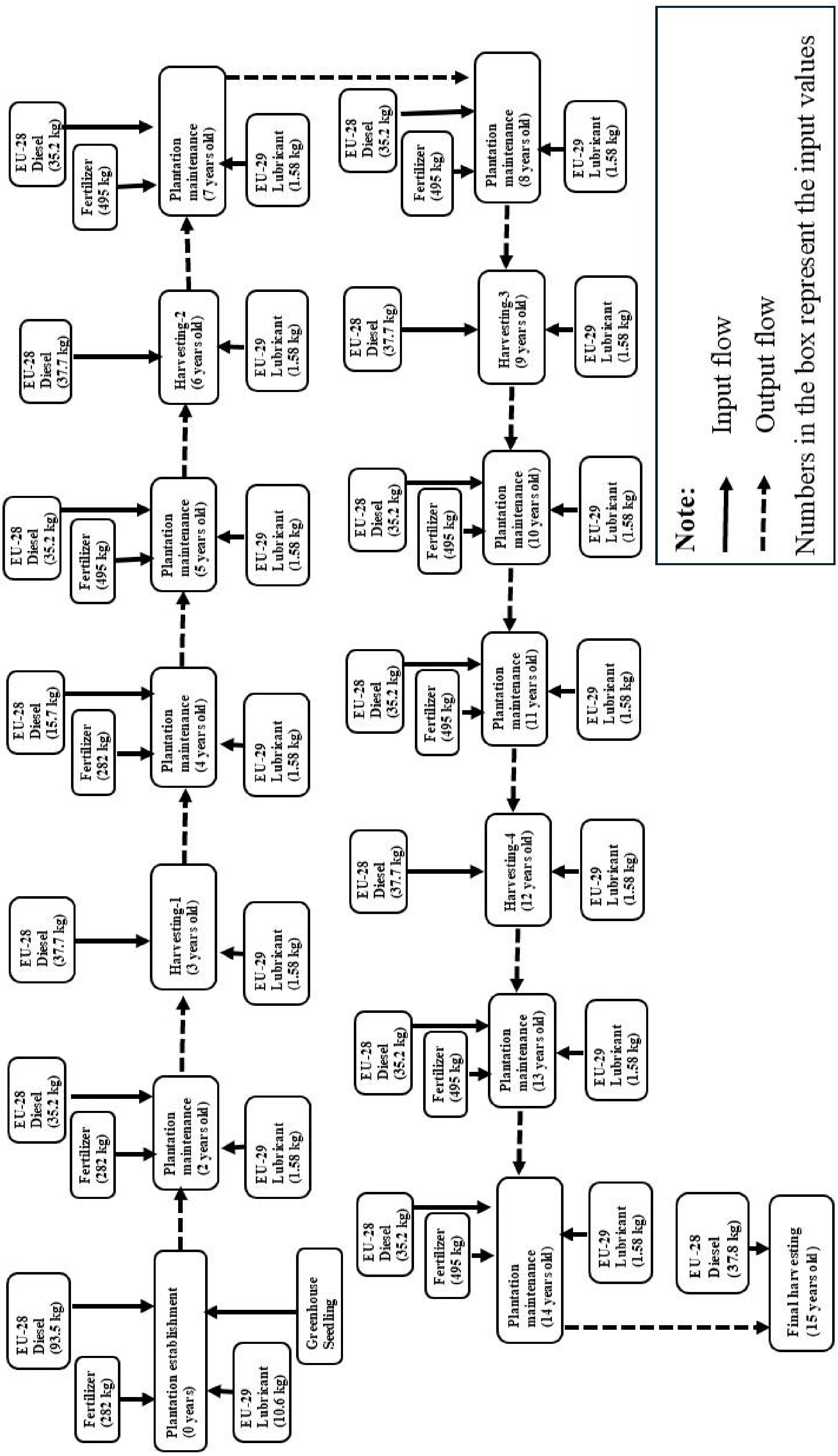

Figure 2. Plan of short-rotation coppice systems for bioenergy production using Sphera LCA for Experts Education License software (Version 9.2.1.68, 2020)

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Table 2. Environmental impacts of the short-rotation coppice system

Research information	This study	Livingstone et al. (2022)	González-García et al. (2012a)		González-García et al. (2012b)
Location	Hungary	Northern Ireland	Italy	Italy	Sweden
Species	poplar and black locust	willow	poplar	poplar	willow
LCA analysis software	Sphera LCA for Experts Education License (Version 9.2.1.68 Education, 2020)	SIMAPRO (Version 9, 2019)	SIMAPRO (Version 7.10, 2011)	SIMAPRO (Version 7.10, 2011)	SIMAPRO (Version 7.10, 2011)
Database	USLCI	Ecoinvent	N.A.	N.A.	Ecoinvent
Rotation	15 years	25 years	10 years	10 years	21 years
First cutting	3 years	2.8 years	2 years (VSRC)	5 years (SRC)	4 years
Number of harvestings	5 times	8 times	5 times	2 times	5 times
Purpose	bioenergy	bioenergy	bioenergy	bioenergy	bioenergy
Tree density	6 700 trees·ha^{-1}	15 000 trees·ha^{-1}	5 560 trees·ha^{-1}	5 560 trees·ha^{-1}	10 000–13 000 trees·ha^{-1}
System boundaries	cradle-to-gate	cradle-to-gate	cradle-to-gate	cradle-to-gate	cradle-to-gate
Stand management	a) plantation establishment b) growth management c) harvesting and liquidation	a) site preparation b) planting c) harvesting	a) site preparation b) planting c) harvesting	a) site preparation b) planting c) harvesting	a) establishment b) cutting c) replacement
Functional unit	per unit area (ha)	per unit area (ha)	per unit area (ha)	per unit area (ha)	per unit area (ha)

CML 2001 impacts	This study	Livingstone et al. (2022)	González-García et al. (2012a)		González-García et al. (2012b)
GWP100 (kg CO_2 eq)	5.96E+03	5.96E+03	–374.7E+03	–433.8E+03	–323.7E+03
Eutrophication potential (kg PO_4^3·ha^{-1})	7.8	7.8	32.89	25.89	159.5
Acidification potential (kg SO_2 eq)	21.6	21.6	140.08	108.87	73.3
Abiotic depletion (kg Sb eq)	0.000171	0.000171	36.18	36.62	52.5
Ozone layer depletion (kg CFC-11 eq)	3.87E-13	3.87E-13	7.13E-4	7.41E-4	1.02
Human toxicity (kg 1,4-DCB eq)	484	484	4.028	4.346	5 236
Freshwater aquatic ecotoxicity (kg 1,4-DCB eq)	11.8	11.8	678	653	1 062
Marine aquatic ecotoxicity (kg 1,4-DCB eq)	3.43E+04	3.43E+04	1.48E+06	1.40E+06	2.6E+03
Terrestrial ecotoxicity (kg 1,4-DCB eq)	4.676	4.676	14.22	11.80	24.8
Photochemical oxidation (kg C_2H_4 eq)	1.82	1.82	0.88	0.91	1.2
Cumulative energy demand (GJ eq)	–	–	85.56	85.78	8 777
Gross energy production (GJ eq)	–	–	3.2E+03	3.7E+03	2.8E+06

CFC – chlorofluorocarbon; C_2H_4 – ethylene; CO_2 – carbon dioxide; DCB – dichlorobenzene; GJ – giga joule; GWP – global warming potential; LCA – life cycle assessment; N.A. – not available; PO_4^3 – phosphate; Sb – antimony; SO_2 – sulphur dioxide; SRC – short rotation coppice; USLCI – United States Life Cycle Inventory; VSRC – very short rotation coppice

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with these findings, similar results have been observed in a variety of contexts, including poplar plantations in Italy (González-García et al. 2012a), willow plantations in Northern Ireland and Sweden (González-García et al. 2012b; Livingstone et al. 2022), softwood and hardwood seedling production in a forest nursery in Pakistan (Yousaf et al. 2024), and arable crop cultivation in Hungary (Polgár et al. 2019).

As illustrated in Table 2, our study has demonstrated that, in comparison to SRC plantations for bioenergy production in Italy, Northern Ireland, and Sweden, our research has indicated a reduced environmental impact. Despite the similarity in system boundaries, functional unit, and system management, disparities in the outcomes of environmental impact analysis are evident among short-rotation coppice plantations dedicated to bioenergy production. The variation in methodological options, reference systems, and data sources has been identified as a contributing factor to these discrepancies in environmental impact results (Perdomo et al. 2021). Perdomo et al. (2021) further elucidated that while the interpretation of results posed challenges, a comprehensive understanding of potential impacts is imperative to ensure the sustainability of the bioeconomy. The distinctive feature of LCA is its capacity to identify potential hotspots and propose alternative solutions to mitigate environmental impacts.

In this study, the identified hotspot is in the first cycle, encompassing activities such as soil preparation and seed planting, growth maintenance, and first harvesting (Figure 3). Notably, the initial cycle exhibited a higher fuel consumption compared to subsequent cycles. According to the data presented in Table 1, the fuel consumption in the first cycle was 109.75 $kg \cdot ha^{-1}$. In contrast, the fuel consumption in the subsequent cycles (second, third, and fourth) was reduced to 51.5 $kg \cdot ha^{-1}$ per cycle. The final cycle exhibited a fuel consumption of 69 $kg \cdot ha^{-1}$.

In detail, the calculation through Sphera LCA for Experts Education License software showed that the dominant environmental impacts come from fuel consumption (Table 3). Fuel and lubricants are sources of emissions that affect the environment. In this study, out of 10 impact categories, 9 impacts were caused by fuel consumption. Furthermore, fertiliser consumption is affected dominantly by global warming potential. Similar findings have also been shown in poplar and oil palm plantations where the application of fertiliser has contributed dominantly to global warming potential (González-García et al. 2012b; Siregar et al. 2015).

As indicated in Table 3, fuel consumption emerged as the predominant input contributing to the environmental impacts during the SRC. Fuel is consumed in on-farm operations, including ploughing, fertiliser and pesticide application, harvesting, and transporting seedlings (Dijkman et al. 2018). Consequently, reducing fuel consumption emerges as a pivotal strategy to mitigate environmental degradation.

The utilisation of fertilisers has been identified as a pivotal strategy for enhancing soil quality post-harvest (Stolarski, Stachowicz 2023). However, the utilisation of fertiliser has been observed to exert deleterious effects on surface water quality (Dijkman et al. 2018). The utilisation of fertilisers also results in the release of ammonia (NH_3), nitrous oxide (N_2O), and nitrogen oxides (NOx) into the atmosphere, contributing to acidification, global warming potential, and eutrophication (Dijkman et al. 2018). Moreover, the release of nitrate (NO_3^-) and phosphate (PO_4^-) during the application of fertiliser contributes to eutrophication in water bodies (Dijkman et al. 2018).

The application of pesticides, encompassing herbicides, fungicides, insecticides, and other chemical compounds, poses a significant threat to non-target species during the process of application. These pesticides often accumulate within the product components, thereby contributing to the development of ecotoxicity and human toxicity (Dijkman et al. 2018). The Sphera LCA for Experts Education License database did not include any pesticide-production processes. However, the usage of pesticides was found to be less than 2 $kg \cdot ha^{-1}$, and the calculation of pesticide avoidance did not result in a significant alteration of the overall environmental impact.

Carbon footprint in short-rotation coppice for bioenergy production. Impact categories in LCA can vary across different life cycle impact assessment methods. However, the impact categories can be used for some items in practice. For instance, in the context of Denmark's LCA of meat production, the researchers' emphasis was placed on three potential environmental impacts: global warming, eutrophication, and acidification (Dijkman et al. 2018). In a review of literature on LCA

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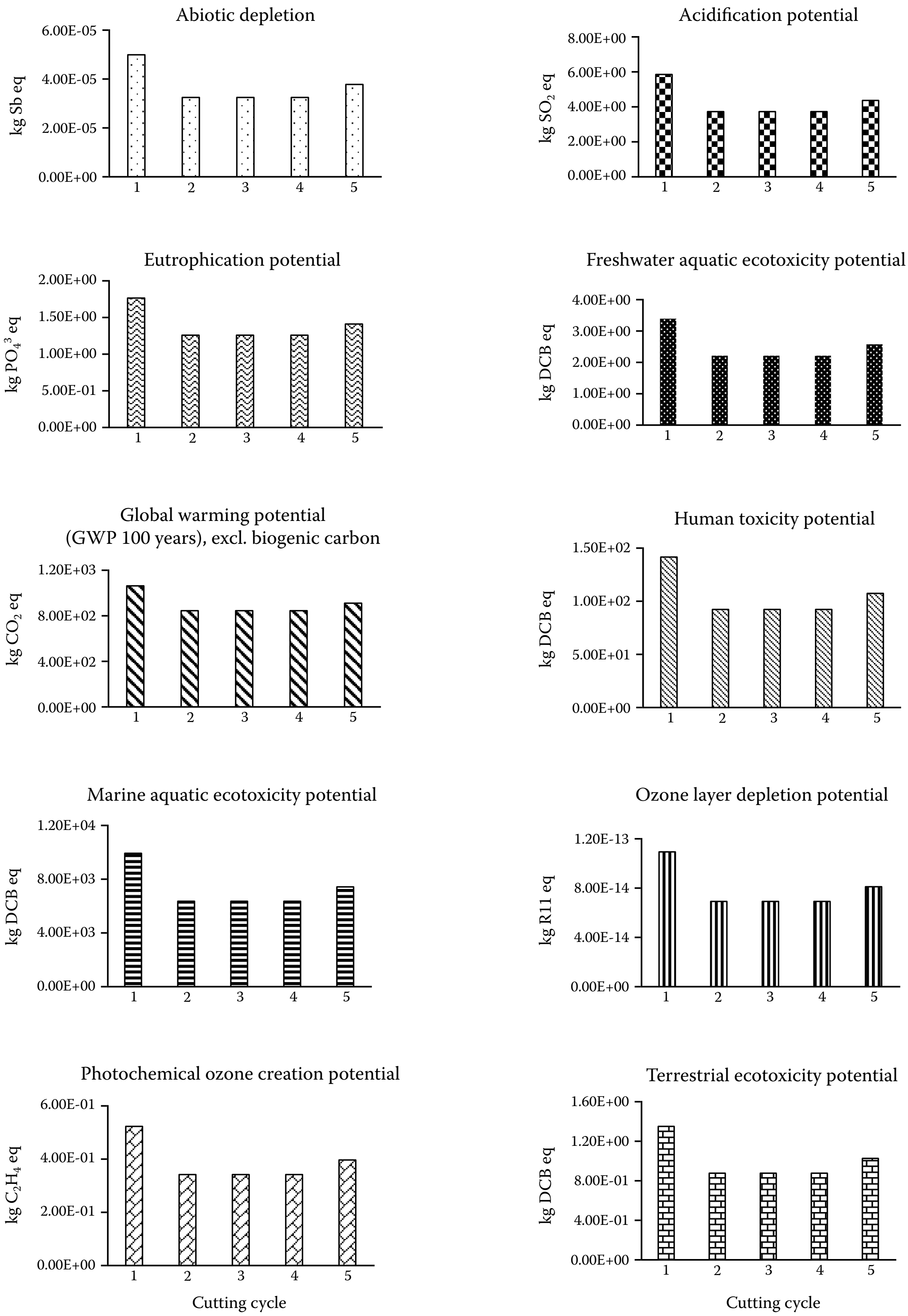

Figure 3. Environmental impacts by cutting cycles according to the CML 2001 method

C_2H_4 – ethylene; CO_2 – carbon dioxide; DCB – dichlorobenzene; PO_4^3 – phosphate; R11 – trichlorofluoromethane; Sb – antimony; SO_2 – sulphur dioxide

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Table 3. Environmental impact distribution based on inputs in short-rotation coppice for bioenergy production (CML 2001 method)

Impact categories	Total	Contribution (%)			
		fuels	lubricants	fertiliser	electricity
Abiotic depletion (kg Sb eq)	1.71E-04	97.99	1.94	0.00	0.07
Acidification potential (kg SO_2 eq)	2.16E+01	95.50	4.48	0.00	0.02
Eutrophication potential (kg PO_4^3 eq)	7.79E+00	90.25	0.36	9.38	0.01
Freshwater aquatic ecotoxicity potential (kg DCB eq)	1.18E+00	62.03	0.08	37.89	0.00
Global warming potential (kg CO_2 eq)	5.96E+03	95.82	3.91	0.25	0.02
Human toxicity potential (kg DCB eq)	4.84E+02	34.17	0.44	65.38	0.01
Marine aquatic ecotoxicity potential (kg DCB eq)	3.43E+03	35.27	0.44	64.28	0.01
Ozone layer depletion potential (kg R11 eq)	3.87E-13	99.19	0.52	0.28	0.01
Photochemical ozone creation potential (kg C_2H_4 eq)	1.82E+00	93.74	5.38	0.28	0.60
Terrestrial ecotoxicity potential (kg DCB eq)	4.68E+00	84.26	14.29	0.00	1.45

C_2H_4 – ethylene; CO_2 – carbon dioxide; DCB – dichlorobenzene; PO_4^3 – phosphate; R11 – trichlorofluoromethane ; Sb – antimony; SO_2 – sulphur dioxide

in forestry, Perdomo et al. (2021) identified a focus on climate change impact categories, with other categories receiving less attention. This research will centre on the environmental impacts of global warming potential (GWP). In the GWP, the effects of greenhouse gas emissions released during the forest management process will be assessed.

The concept of carbon footprint came from Wackernagel and Rees (1996) as a subset of the terminology of ecological footprint. The conceptual development of the carbon footprint is intrinsically linked to the GWP, which is a critical component of life cycle impact assessment (Durojaye et al. 2020). Moreover, the ISO 14044 stipulates that the GWP is expressed mathematically relative to CO_2, with the unit designated as the carbon dioxide equivalent (CO_2 eq). Consequently, the carbon footprint constitutes the value of global warming potential (GWP 100 years), signifying the reference carbon emissions from a bioenergy production process in short-rotation coppice plantation.

The life cycle impact analysis output in the Sphera LCA for Experts Education License is based on the CML 2001, Environmental Footprint (EF) 3.0, IPCC AR5, and ReCiPe 2016 methodologies. The total carbon footprint of biomass production in SRC plantation for 15-year rotation for CML 2001, EF 3.0, IPCC AR5, and ReCiPe 2016 midpoint is 5.96E+03, 6.29E+03, 5.97E+03, and 4.25E+03 kg CO_2 eq, respectively. It is important to note that the application of different methods results in the generation of different values for impact categories (Perdomo et al. 2021). However, the trends of carbon footprint value in different life cycle impact assessment methods (CML 2001, EDIP, EF, TRACI, and ReCiPe 2016) in the same research site and production processes have shown similar trends (Koch et al. 2023). A review of the literature conducted by Martín-Gamboa et al. (2020) revealed that the most frequently utilised life cycle impact assessment methods by researchers to analyse the carbon footprint were IPCC and CML 2001. Polgár et al. (2018, 2019) have employed the CML 2001 methods to assess the carbon footprint in different harvesting systems in short-rotation energy plantations in Hungary. The value of the carbon footprint in understanding the potential environmental impacts of greenhouse gas emissions is vital.

To this end, a detailed analysis was conducted, focusing on the carbon footprint contribution from each cutting cycle. The carbon footprint from the CML 2001 method for the first, second, third, fourth, and final cycles is 1.40E+03, 1.05E+03, 1.17E+03, 1.17E+03, and 1.17E+03 kg CO_2 eq, respectively. The LCA plan (Figure 3) indicates that the primary carbon footprint sources are fertiliser, fuel, and lubricant consumption. The carbon footprint based on consumption of fuels, lubricants, fertiliser, and electricity in black locust and poplar short-rotation coppice management systems were 2.10E+03, 2.60E+01, 3.83E+03, and 6.43E-01 kg CO_2 eq, respectively. The combustion of machinery utilised in the cultivation process has resulted in the re-

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lease of carbon emissions into the atmosphere (González-García et al. 2012a, b). Furthermore, according to González-García et al. (2012b), the carbon footprint of poplar with inorganic fertiliser was more significant than that of poplar plantation management without inorganic fertiliser. A similar finding was also found in Indonesia, where the dominant contribution to the carbon footprint in oil palm plantations is fertiliser, which accounts for around 50.46% of the total carbon footprint (Siregar et al. 2015).

CONCLUSION

Forest operations in bioenergy production from short-rotation coppice (SRC) systems have resulted in potential environmental impacts. Based on LCA analysis, the impacts categories during the 15 years of SRC to produce bioenergy are abiotic depletion, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity potential, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, ozone layer depletion potential, photochemical ozone creation potential, and terrestrial ecotoxicity potential. Compared to other SRCs, the environmental impacts in our study were lower than those of others.

Furthermore, the total carbon footprint in the short-rotation coppice management system during the 15 years is 5.96E+03 kg CO_2 eq The highest contribution comes from the first cycles as 1.40E+03. Furthermore, cycles 2, 3, 4, and 5 contribute to the carbon footprint as 1.05E+03, 1.17E+03, 1.17E+03, 1.17E+03 kg CO_2 eq, respectively. Moreover, the carbon footprint based on the consumption of fuel, lubricants, fertiliser, and electricity was 2.10E+03, 2.60E+01, 3.83E+03, and 6.43E-01 kg CO_2 eq, respectively.

In the future, the consumption of fuel, lubricants, fertilisers, and pesticides should be reduced to minimise the negative environmental impacts. Research on life cycle assessment in the forestry sectors should be applied in different plantation management systems to better understand the potential environmental impacts and alternative solutions.

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