

LIFE CYCLE ASSESSMENT OF BLACK LOCUST AND POPLAR TIMBER PRODUCTION IN HUNGARY

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LIFE CYCLE ASSESSMENT OF BLACK LOCUST AND POPLAR TIMBER PRODUCTION IN HUNGARY. Forests play a vital role in carbon sequestration and storage through photosynthesis. However, in Hungary, only a few studies have elaborated on the potential carbon emissions that are released during forest operations. The objective of this study was to assess the potential environmental impacts (including the carbon footprint) of forest operation in timber production. Data collection and data analysis followed the life cycle assessment (LCA) procedure in ISO 14044. Furthermore, for calculating the result of the life cycle impact assessment, we used the Sphera LCA for Experts Education License version 9.2.1.68 Software. The findings showed that fuel consumption and agrochemicals applications (fertilizer and pesticides) drive key impact categories-acidification, resource depletion, and global warming potential- with harvesting identified as the largest contributor to the overall environmental impact. Harvesting activity has contributed more dominantly to abiotic depletion, acidification potential, global warming potential, human toxicity potential, ozone layer depletion potential, and terrestrial ecotoxicity potential than thinning and plantation establishment activities. Furthermore, based on the input sources, applications of fertilizer have contributed significantly to global warming potential, followed by fuels and lubricants, respectively. According to research findings, the application of fertilizer and fuel consumption should be reduced to minimize the lower environmental impacts.

Keywords: Life Cycle Assessment, Carbon footprint, Climate change mitigation, Environmental impacts, long-rotation management systems

PENILAIAN DAUR HIDUP PRODUKSI KAYU BLACK LOCUST DAN POPLAR DI HONGARIA. Hutan terbukti memiliki peran penting dalam penyerapan dan penyimpanan karbon melalui fotosintesis. Akan tetapi, di Hongaria, hanya sedikit penelitian yang menguraikan potensi emisi karbon yang dilepaskan selama kegiatan kehutanan. Tujuan dari penelitian ini adalah untuk menilai potensi dampak lingkungan (termasuk jejak karbon) dari kegiatan kehutanan dalam produksi kayu. Pengumpulan dan analisis data mengikuti prosedur penilaian daur hidup (life cycle assessment/LCA) dalam ISO 14044. Selanjutnya, untuk menghitung hasil penilaian dampak daur hidup, kami menggunakan perangkat lunak Sphera LCA for Experts Education License versi 9.2.1.68. Hasil yang diperoleh menunjukkan bahwa konsumsi bahan bakar dan aplikasi agrokimia (pupuk dan pestisida) dalam kegiatan kehutanan telah menghasilkan kategori dampak penting-pengasaman, penipisan sumber daya, dan potensi pemanasan global- dimana aktivitas pemanenan teridentifikasi sebagai penyumbang terbesar dari dampak tersebut. Aktivitas pemanenan telah memberikan kontribusi yang lebih dominan terhadap penipisan abiotik, potensi pengasaman, potensi pemanasan global, potensi toksisitas manusia, potensi penipisan lapisan ozon, potensi ekotoksitas terestrial daripada kegiatan penjarangan dan pembangunan hutan tanaman. Lebih jauh, berdasarkan sumber input, penggunaan pupuk memiliki kontribusi yang signifikan terhadap potensi pemanasan global, diikuti oleh bahan bakar dan pelumas. Berdasarkan hasil penelitian, penggunaan pupuk dan konsumsi bahan bakar harus dikurangi untuk meminimalkan dampak negatif terhadap lingkungan.

Kata kunci: Penilaian daur hidup, Jejak karbon, Mitigasi perubahan iklim, Dampak lingkungan, Sistem pengelolaan daur panjang

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I. INTRODUCTION

Forest-based production systems play a crucial role in supplying raw materials while also contributing to climate change mitigation. In Hungary, black locusts and poplars play a vital role in timber production, supplying the wood industry. Poplar plantations in Hungary are the second largest in Europe and are used for some wood industries, such as packaging (pallets and boxes), furniture, plywood, fiber, and energy purposes (Komán et al., 2023). Furthermore, apart from being cultivated as a windbreak and pioneer vegetation for reclamation, due to its good physical and mechanical properties, black locust wood is also used for construction materials and bioenergy (Bijak & Lachowicz, 2021). Black locusts also supply around 21% of the total wood supply in Hungary (Nicolescu et al., 2018).

Cultivation of fast-growing species, especially non-native species, should consider many aspects, including economic, social, and ecological considerations. Black locust and poplar plantation in short-rotation coppice systems in Hungary have shown their ability to sequester carbon emissions from the atmosphere and store it in the above and below-ground biomass (Mulyana et al., 2024). In Germany, black locusts and poplars are promising species for mining reclamation (Quinkenstein & Jochheim, 2016).

Apart from black locusts securing the wood supply for industries, black locusts are also associated with environmental impacts. As the pioneer vegetation, black locusts have adapted to marginal land, and it is threatening the native dry and semi-dry grassland species in Central Europe (Vítková et al., 2017). Black locusts and poplar log production in short-rotation systems for bioenergy purposes have resulted in lower impacts on the environment, especially in releasing greenhouse gas (GHG) emissions to the atmosphere (Morales-Vera et al., 2022; Żelazna et al., 2019). Global warming potential (GWP) of bioenergy production (poplar and black locust) with short-rotation coppice system

in Hungary is 5.9 ton CO₂ eq/ha (Mulyana et al., 2025). Not only for bioenergy purposes, multifunctional poplar plantations (roundwood and woodchips) also release GHG emissions of around 45.1 kg CO₂ eq/oven dry ton whole tree (Laina et al., 2022). Even though black locust and poplar plantations have been proven to have lower impacts on the environment, research on life cycle assessment (LCA) on forestry operations in Hungary is still limited (Mulyana et al., 2023).

Furthermore, the objective of this study was to describe the potential environmental impacts on timber production of black locust and poplar plantations in Hungary. Specifically, we also elaborate on the environmental impacts based on activities (plantation establishment, thinning, and harvesting) and inputs (fuel, lubricant, fertilizer, and pesticide) in the forest operations to produce the timber from black locust and poplar plantations in Hungary.

II. MATERIAL AND METHOD

Black locust and poplar plantations can be managed to supply round wood or bioenergy. Globally, the poplar plantations that are dedicated to multipurpose, timber production, environmental protection, and biomass production were 18.3, 9.4, 2.9, and 0.9 million ha, respectively (Lovarelli et al., 2018). Furthermore, Lovarelli et al. (2018) explained that traditional poplar plantation (TPP) was different from the short-rotation coppice (SRC) or short-rotation forestry (SRF) systems in the length of rotation, wood utilization, tree management, and harvesting method. Data on black locust in Central Europe is still limited because black locust is an invasive species and its exact distribution is not yet known (Vítková et al., 2017).

A. Goal and Scope Definition

The objective of this study was to evaluate the environmental impact of black locust and poplar timber production for industrial purposes in Hungary. The intended audience

of this study are policymakers, forest managers, and researchers working in life cycle assessment and forest-based bioeconomy systems. The results of this study are intended to support decision-making related to sustainable timber production and its utilization. Furthermore, this study provides a methodological and data foundation for future LCA studies, especially for improving country-specific inventory data for the timber production system under long-rotation management. A number of studies conducted in European countries have demonstrated that timber production has led to various environmental consequences, including acidification, eutrophication, resource depletion, human toxicity (Dias et al. 2022; Lovarelli et al. 2018), and global warming potential (Prinz et al. 2018; Proto et al. 2017; Spinelli and Moura 2019). The LCA study on timber production has been conducted for various tree species, including eucalyptus (Dias et al. 2022), cryptomeria (Dias et al. 2022), birch (Kuka et al. 2020), pine (Bernardi et al. 2022; Dias et al. 2022; Kuka et al. 2019), and poplar

(Laina et al. 2022; Lovarelli et al., 2018).

The boundaries of the system under study varied across LCA studies of wood production, affecting the environmental impact assessment (Dias et al. 2022). In the context of birch and pine wood production in Latvia, the subsystems of timber production encompass seed production, seedling production, silvicultural operations, and logging operations (Kuka et al. 2019, 2020). In Japan, forest operations for timber production (Japanese cedar, hinoki cypress, Japanese larch, and Sakhalin fir) were grouped into planting, thinning, and final felling (Nakano et al. 2018). Conversely, in the context of industrial pine roundwood production in Brazil, forest operations were classified into the following categories: soil preparation, seedling plantation, forest management, forest harvesting, and infrastructure establishment (Ferro et al. 2018). In this research, the subsystems in timber production were divided into plantation establishment, growth maintenance, thinning, and harvesting (Figure 1).

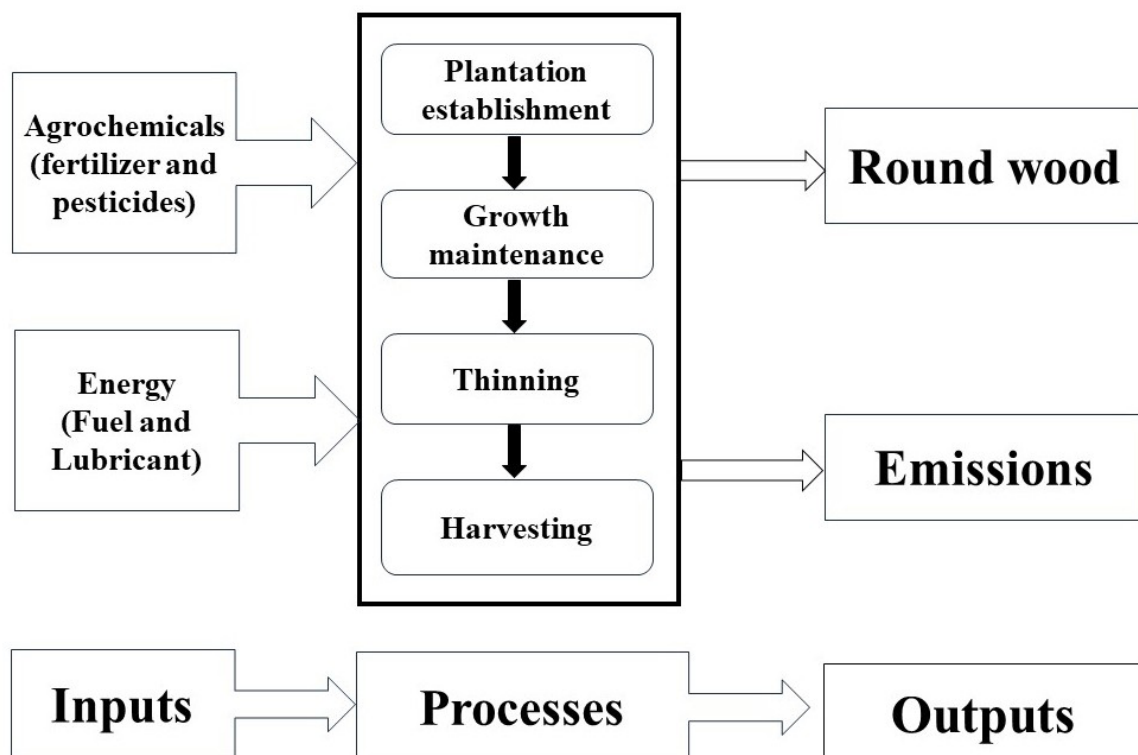


Figure 1. The system boundary of timber production

Generally, the forest operations in timber production can be described as follows:

- Plantation establishment: in plantation establishment, the activities are seed production and site preparation/pre-planting (Table 1). Seed production involved less utilization of mechanization (Kuka et al. 2019, 2020), but the site preparation activities for plowing, harrowing, and mechanical hole opening used some tractors (Bacenetti et al. 2016; Chiarabaglio et al. 2020).
- Growth maintenance: Growth maintenance activities include agro-technical tending and plant protection (Kuka et al. 2019, 2020).
- Thinning: In other studies, such as Kuka et al. (2019, 2020), the harvesting operation included thinning activities. In this study, the thinning operation is separated from harvesting activities because thinning has been conducted many times during a cycle rotation. In the thinning operation, the machines were applied to cut the trees.
- Harvesting: In this study, the harvesting operation is clear-cutting and conducted at the rotation's end. Harvesting methods in timber production are whole tree, tree length, and cut-to-length (De Francesco et al. 2022; Schweier et al. 2019; Spinelli et al. 2022). The purpose of the cutting method in the harvesting operation of the industrial

plantation is efficiency (Farooq et al. 2021).

According to Sahoo et al. (2021), the system boundary of cradle-to-grave in timber production can be divided into some groups as follows:

- Cradle-to-gate: the activities started with seedling production, forest management, harvesting, and transporting logs to the manufacturer.
- Gate-to-gate: the activities were timber yarding, sawing, drying, and transporting wood products to consumers.
- Gate-to-grave: the activities were transport to warehouses, transport to installation sites, consumer, demolition, transport to disposal site, and disposal of wood products' waste.

B. Functional Unit

The decision to employ a functional unit is a pivotal phase in the LCA process, as it entails assessing inputs and outputs. In the context of LCA studies in forestry operations, the functional unit has been examined through various parameters, including mass, energy, time, and area size (Mulyana and Hemida 2023). In addition, certain researchers have employed the functional unit of 1 m³ of timber production (Kuka et al. 2019; Proto et al. 2017; Sahoo et al. 2021). However, it should be noted that data collection for these studies was conducted within a 1 ha forest area, and the resulting data

Table 1. Characteristic in black locust and poplar timber production

Location	Species	System boundary	Silvicultural activities						References
			Seed production	Site preparation	Growth maintenance	Thinning	Harvesting	Others	
Brazil	<i>Pinus oocarpa</i>	Cradle-to-gate	√	√	√	√	√		Ferro et al. (2018)
Japan	<i>Abies sachalinensis</i> , <i>Chamaecyparis obtuse</i> , <i>Cryptomeria japonica</i> , <i>Larix kaempferi</i>	Cradle-to-gate	√	√	√	√	√		Nakano et al. (2018)
Latvia	<i>Pinus sylvestris</i>	Cradle-to-gate	√	√	√	√	√		Kuka et al. (2019)
Latvia	<i>Betula</i> spp	Cradle-to-gate	√	√	√	√	√		Kuka et al. (2020)
Italy	<i>Castanea sativa</i>	Gate-to-gate					√		Proto et al. (2017)
Portugal	<i>Pinus pinaster</i> , <i>Eucalyptus globulus</i> , <i>Cryptomeria japonica</i>	Cradle-to-gate		√	√	√	√		Dias et al. (2022)
USA	<i>Sequoia sempervirens</i>	Cradle-to-grave	√	√	√	√	√	√	Sahoo et al. (2021)

were subsequently converted to the specified 1 m³ of harvested wood (Kuka et al. 2020). Bernardi et al. (2022) employed the functional unit of 1 ha to assess the environmental impacts of logging operations in the Calabrian pine high forest in Italy.

According to Martínez-Blanco et al. (2015), the functional unit serves as the primary unit of analysis in LCA. This study employed the functional unit of 1 ha of timber production, aligning with the methods of Bacenetti et al. (2014, 2016b) and Cantamessa et al. (2022). These researchers utilize the functional unit of area (1 ha) to examine the LCA of agricultural production systems. Additionally, Polgár et al. (2018) employed the functional unit of 1 ha to assess the carbon footprint of various harvesting methods in energy plantations in Hungary.

C. Life Cycle Inventory

According to the International Standardization Organization 14044 (2006), life cycle inventory (LCI) is a phase in which data of both qualitative and quantitative nature is collected within the system boundary. The LCI is a critical component of life cycle assessment (LCA) processes, as it can significantly impact the study's results and conclusions (Kuka et al. 2020). Furthermore, Kuka et al. (2020) described that the LCI phase is often time-consuming due to the need for precise data collection. Despite the challenges associated with data collection, various methods, including measurement, calculation, and approximation for proxy data, can be employed to develop the LCI (Bjørn et al. 2018).

However, data collection for LCI is challenging due to limited data availability and accessibility. For instance, under Latvia's government regulations, harvesting pine trees is permitted when they reach ages 101–120 years. To obtain information on seedling production, planting establishment, and forest management of pine forests during the period 1900–2020, researchers relied on assumptions and estimations based on current silvicultural

practices (Kuka et al. 2019). Furthermore, Kuka et al. (2019) recommended that to get a more precise, comprehensive, and representative result of LCA, the assumptions should be avoided to reduce bias.

In this study, we employed the yield tables of black locust and poplar to estimate the volume of thinning and harvesting (Rédei et al. 2012, 2014). The utilization of a local yield table construction system has been applied in the collection of LCI data in the LCA of round wood production (*Abies sachalinensis*, *Chamaecyparis obtusa*, *Cryptomeria japonica*, and *Larix kaempferi*) in Japan (Nakano et al. 2018). Furthermore, data on fossil fuel consumption for machinery and agricultural chemicals (pesticides and fertilizer) can be collected from literature or databases (Oneil and Puettmann 2017; Zhang et al. 2020). In this research, due to the limitation of data on fuel consumption, we follow Cantamessa et al. (2022) to estimate fuel consumption using equation 1. Estimation through calculations from many data sources has also been applied in some research, such as in the Northwest United States (Oneil and Puettmann 2017) and China (Zhang et al. 2020)

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

Where F is fuel consumption (kg/ha), Sc is specific fuel consumption (fixed to 0.25 kg/Kwh), P is maximum engine power (Kw), d is power utilization in %, and t is time (hours).

Power utilization in plantation establishment was 60%, and the maximum engine power ranged from 55–85 Kw (Cantamessa et al. 2022; Fiala and Bacenetti 2012). Moreover, the engine power of machinery for thinning and harvesting operations was 50–124 Kw, and the power utilization was from 64% to 67% (Cantamessa et al. 2022; De Francesco et al. 2022; Eisenbies et al. 2017; Spinelli et al. 2022). Furthermore, the consumption of pesticides was 4.5 L/ha (Glyphosphate), 4.8 L/ha (Pyretroid-comp.), 18.0 L/ha (fungicide), and fertilizer was 495 Kg/ha (urea superphosphate), 250 kg/ha (KCl) (González-García et al. 2014; Lovarelli et al. 2018). Lube consumption (hydraulic and

transmission oil) for thinning and harvesting operations was 30 l/1,000m³ (Athanasiadis et al. 1999).

D. Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is calculated using software or manual calculation based on life cycle inventory data (Rosenbaum et al. 2018). The Sphera LCA for Experts Education License version 9.2.1.68. Software is a popular software in the study of life cycle assessment in European countries. The Sphera LCA for Experts Education License version 9.2.1.68. database modeling has been widely used by academia, researchers, practitioners, and policymakers to analyze the life cycle assessment of product processes (Kupfer et al. 2021). For example, Sphera LCA for Experts Education License version 9.2.1.68. Software has been used to analyze the LCA of forest operations, in both short- and long-rotation systems, in Hungary (Polgár 2023; Polgár et al. 2018, 2019) and Italy (Pierobon et al. 2015).

Furthermore, this study developed the plan or framework for product processes and life cycle impact assessment in Sphera LCA for Experts Education License version 9.2.1.68. Software (Figure 2).

III. RESULT AND DISCUSSION

A. Environmental impacts potential in timber production

Black locust and poplar plantations have been cultivated for a more extended rotation and with a reduced planting density compared to bioenergy production. According to the table yield of black locust (Rédei et al. 2014) and poplar (Rédei et al. 2012), the plantations were cultivated for 45 years. The silvicultural activities undertaken during the 45-year rotation period encompass the establishment of the plantations, maintenance of growth, and harvesting after the rotation (Table 2). The silvicultural practices employed during the 45-year rotation included the application

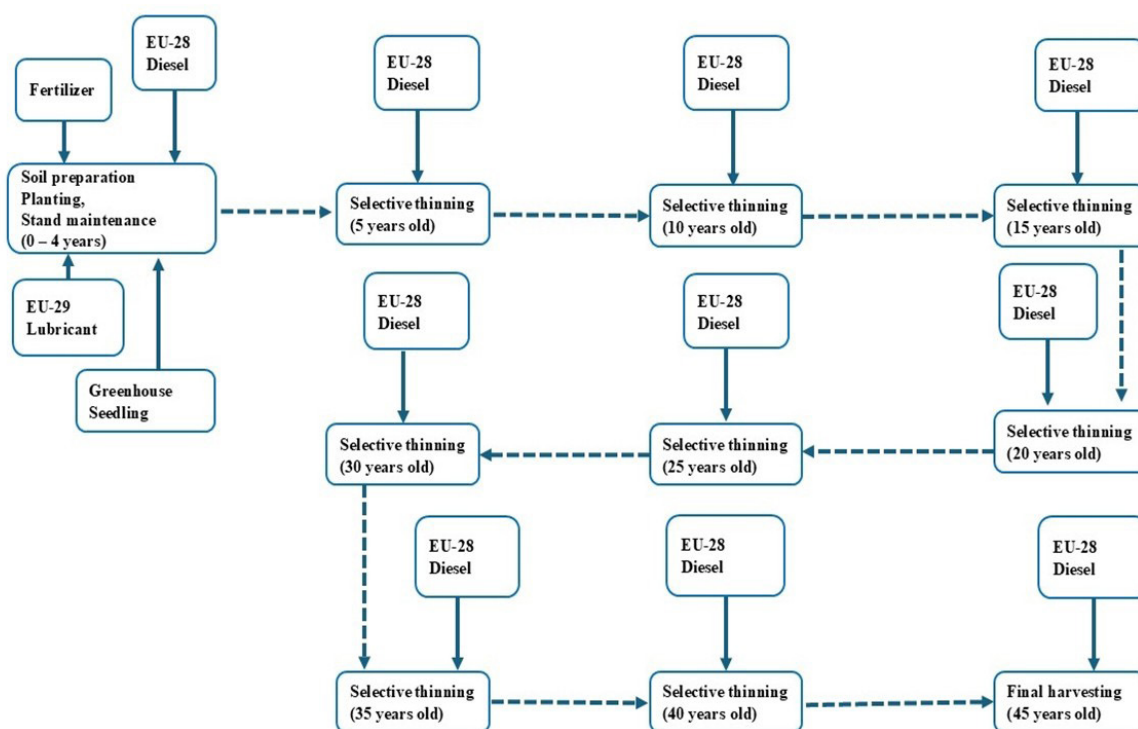


Figure 2. LCA plan of timber production using Sphera LCA for Experts Education License version 9.2.1.68. Software.

of fertilizers and pesticides in the initial year, followed by thinning activities at ages 5, 10, 15, 20, 25, 30, 35, and 40 years.

As illustrated in Table 2, the values of the environmental impact categories exhibited variation among the research sites. The values of these categories were found to be influenced by the inputs utilized during forestry operations. As presented in Table 2, the predominant environmental impact categories in timber production in black locust and poplar plantations were global warming potential (GWP) and ecotoxicity. In this study, the GWP for black locust and poplar were determined to be $4.0 \text{ E}10+03$ and $4.3 \text{ E}10+03 \text{ kg CO}_2 \text{ eq}$, respectively. Moreover, the GWP for poplar plantations in Italy ranged from $7.2 \text{ E}10+03$ to $10.5 \text{ E}10+03 \text{ kg CO}_2 \text{ eq}$ (Cantamessa et al. 2022; Chiarabaglio et al. 2020). According to Huang et al. (2015), the primary sources of carbon emissions from 1960 to 2009 were biomass

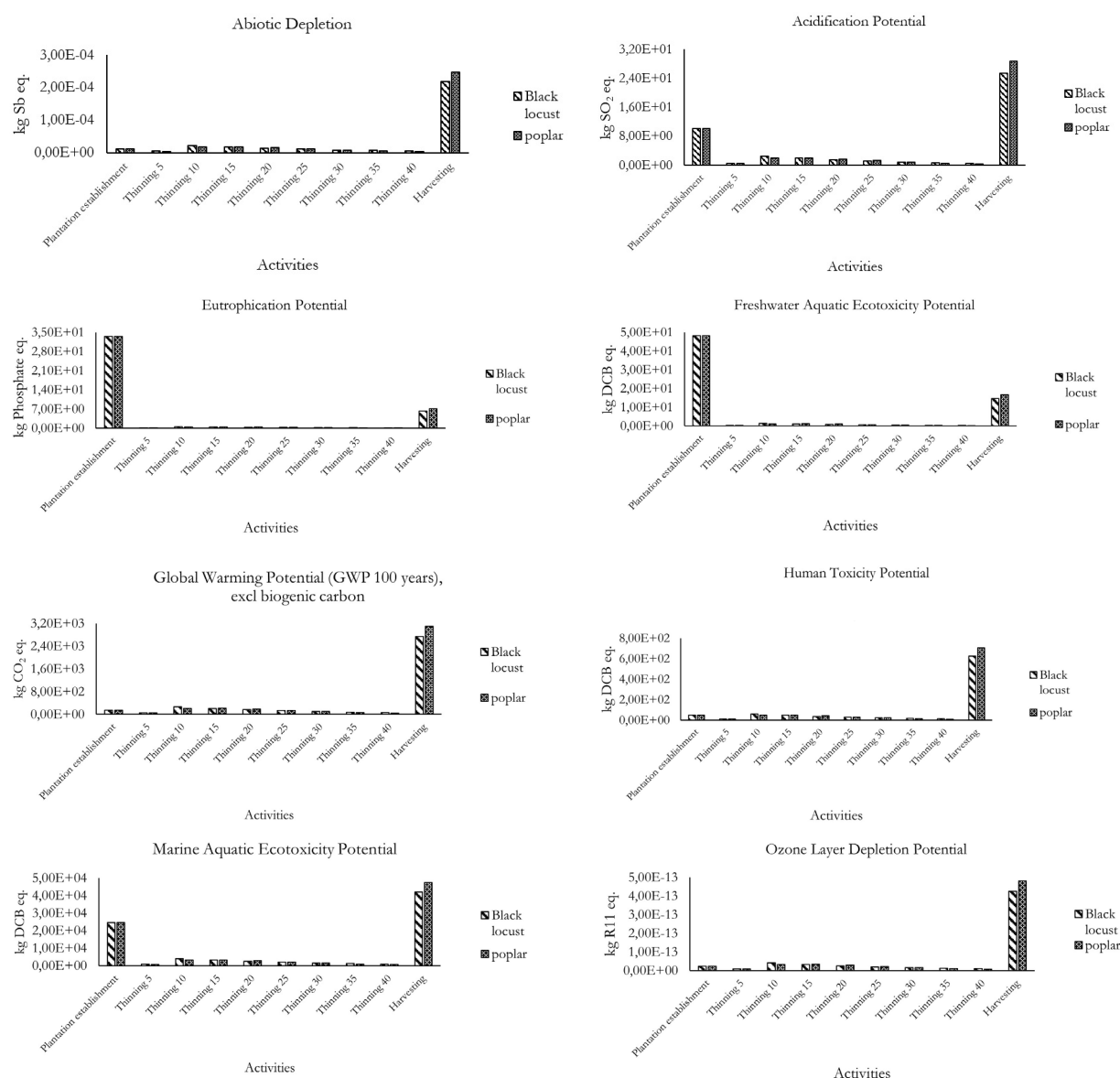
combustion/wildfires and fuel consumption. A detailed calculation using the Sphera LCA for Experts Education License version 9.2.1.68 Software revealed that the GWP is attributed to the use of mechanized methods in harvesting operations, thinning, and fuel consumption in plantation establishments.

In detail, the result of impact categories from Sphera LCA for Experts Education License version 9.2.1.68. Software showed that harvesting activity contributed to many impact categories such as abiotic depletion, acidification potential, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, ozone layer depletion potential, photochemical ozone creation potential, and terrestrial ecotoxicity potential (Figure 3). Meanwhile, the fertilizer application affected the eutrophication potential and the freshwater aquatic ecotoxicity potential.

Table 2. Environmental impacts of timber production for industrial purposes

	This study		Cantamessa et al. (2022)	Chiarabaglio et al. (2020)
Location	Hungary	Hungary	Italy	Italy
Species	Poplar	Black locust	Poplar	Poplar
LCA analysis software	Sphera LCA for Experts Education License version 9.2.1.68.	Sphera LCA for Experts Education License version 9.2.1.68.	SIMAPRO v.8.0	SIMAPRO v.8.0
Database	USLCI	USLCI	Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI	Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI
Rotation	45 years	45 years	10 years	10 years
Purpose	Industrial	Industrial	Industrial (veneer)	Industrial
Soil	Sandy loamy	Sandy loamy	Sandy loamy	Sandy loamy
Tree density	400 trees/ha	400 trees/ha	250 – 300 trees/ha	250 – 300 trees/ha
System boundaries	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate
Stand management	a). plantation establishment b). growth management c). harvesting	a). plantation establishment b). growth management c). harvesting	a). soil preparation and planting b). cultivation c). harvesting	a). soil preparation and planting b). cultivation c). harvesting

	This study		Cantamessa et al. (2022)	Chiarabaglio et al. (2020)
Functional unit	Per unit area	Per unit area	Per unit area (ha)	Per unit area (ha)
GWP100 (IPCC) (kg CO ₂ eq)	(ha)	(ha)	10.5E+03	7.3E+03 (I-214 clones) 7.2E+03 (MSA clones)
	4.3E10+03	4.0E10+03		
ReCiPe midpoint				
- Terrestrial acidification (kgSO ₂ eq)	36.2	34.3	48.3	n.a
- Terrestrial ecotoxicity (kg 1,4-DCB)	1,260	1,235	18,503	
- Freshwater ecotoxicity (kg 1,4-DCB)	4,708	4,655	165	
- Marine ecotoxicity (kg 1,4-DCB)	21,756	21,432	205	
- Human toxicity (kg 1,4-DCB)	350.9	345.0	6,254	
- Water consumption (m ³)	-	-	17,460	
- Stratospheric ozone depletion (kg CFC11 eq)	0.0009	0.0008	0.016	
- Land use (m ² a crop eq)	190.2	177.6	140.4	
- Fossil resources scarcity (kg oil eq)	1,287.3	1,201.3	3,431.3	
Yield (m ³ /ha)	425	378	158	n.a



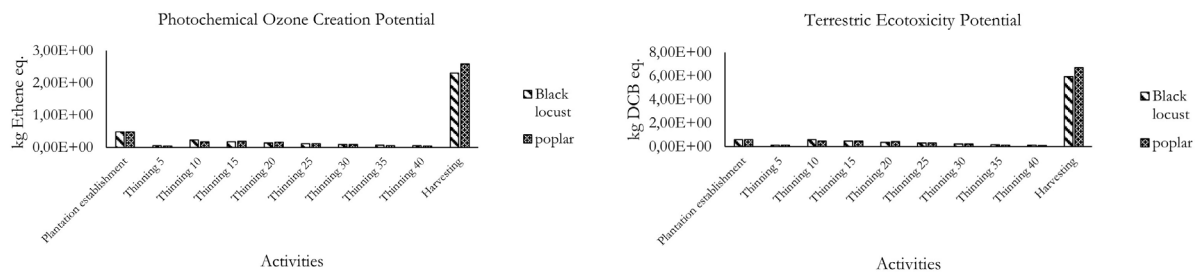


Figure 3. Environmental impacts during long-rotation plantation (45 years) in the CML method.

Table 3. Environmental impact distribution based on inputs in timber production (CML 2001 method)

Impact categories	Unit	Poplar			Black locust		
		Fuels	Lubricants	Fertilizer	Fuels	Lubricants	Fertilizer
Abiotic Depletion (ADP elements)	kg Sb eq.	3.39E-04	1.34E-07	0.00E+00	3.17E-04	1.34E-07	0.00E+00
Acidification Potential (AP)	kg SO ₂ eq.	3.94E+01	3.16E-03	8.91E+00	3.68E+01	3.16E-03	8.91E+00
Eutrophication Potential (EP)	kg Phosphate eq.	9.78E+00	2.47E-04	3.32E+01	9.13E+00	2.47E-04	3.32E+01
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg DCB eq.	2.29E+01	1.86E-02	4.74E+01	2.14E+01	1.86E-02	4.74E+01
Global Warming Potential (GWP 100 years), excl biogenic carbon	kg CO ₂ eq.	4.25E+03	1.05E+00	0.00E+00	3.97E+03	1.05E+00	0.00E+00
Human Toxicity Potential (HTP)	kg DCB eq.	9.70E+02	1.01E-01	1.84E+01	9.06E+02	1.01E-01	1.84E+01
Marine Aquatic Ecotoxicity Potential (MAETP)	kg DCB eq.	6.51E+04	7.44E+01	2.24E+04	6.07E+04	7.44E+01	2.24E+04
Ozone Layer Depletion Potential (ODP, steady state)	kg R11 eq.	6.60E-13	2.23E-15	0.00E+00	6.16E-13	2.23E-15	0.00E+00
Photochemical Ozone Creation Potential (POCP)	kg Ethene eq.	3.56E+00	4.67E-04	3.56E-01	3.32E+00	4.67E-04	3.56E-01
Terrestrial Ecotoxicity Potential (TETP)	kg DCB eq.	9.19E+00	4.44E-03	2.66E-01	8.58E+00	4.44E-03	2.66E-01

In this study, the detrimental environmental impacts have resulted dominantly from the harvesting operations. According to Kuka et al. (2019, 2020), logging operations producing pine and birch timber in Latvia resulted in more harmful environmental impacts than other silvicultural activities. A similar finding is reported by Klein et al. (2015), which shows that timber production has had detrimental environmental impacts. Harvesting using different logging methods (shortwood, chipwood, and whole-tree harvesting systems) has also negatively affected the environment (Laina et al. 2022; Laschi et al. 2016). The most significant greenhouse gas emissions in timber production of cedar (*Cryptomeria japonica*), hinoki cypress (*Chamaecyparis obtusa*),

larch (*Larix kaempferi*), and Sakhalin fir (*Abies sachalinensis*) in Japan resulted from harvesting operations (Nakano et al. 2018).

As shown in Table 3, the analysis indicates that fuel consumption had the dominant environmental impact during forestry operations. In this study, the carbon emissions were almost entirely attributable to fuel consumption. The significance of fuel consumption in mechanized on-farm operations, such as site preparation, fertilizer and pesticide application for growth maintenance, and timber harvesting, has been previously documented (Dijkman et al. 2018). Moreover, the carbon emission from fuel combustion and combined heating and power in China's forestry-pulp and paper industry resulted in 6.78 E+06 CO₂ eq (Zhao et al. 2019).

Consequently, reducing fuel consumption is a pivotal strategy to mitigate environmental degradation.

B. Carbon footprint in timber production

Despite the fact that the definition of carbon footprint remains open to interpretation, the concept has gained acceptance as a means of quantifying greenhouse gas (GHG) emissions released into the atmosphere, expressed as CO₂ equivalent (Choi et al. 2015). Initially, the concept of carbon footprint was introduced by Wackernagel and Rees (1996) as ecological footprint. As a component of the ecological footprint, the primary metric for calculating the carbon footprint is the average forest carbon sequestration (Mancini et al. 2016). In the development of the concept of the carbon footprint, it was incorporated into the environmental impact categories of life cycle assessment as global warming potential (Durojaye et al. 2020). Consequently, this study used the global warming potential to elucidate the carbon footprint of forest operations in timber production.

The carbon footprint associated with forest operations is attributable to two primary sources: indirect (off-site) and direct (on-site) emissions. Direct carbon emissions from forest operations stem from fuel combustion, while indirect emissions arise from electricity

or thermal energy consumption (Zhao et al. 2019). It is important to note that fertilizer use contributes significantly to the agricultural sector's carbon footprint (Siregar et al. 2015). This study used a comprehensive approach to estimate the carbon footprint, including both direct and indirect emissions.

As depicted in Figure 4, the contribution of carbon emissions from establishing black locust plantations, thinning, and harvesting is 4%, 27%, and 69%, respectively, of the total carbon emission. In a similar analysis of a poplar plantation, the distributions of carbon emissions during plantation establishment, thinning, and harvesting were 3%, 24%, and 73% of the total carbon emissions, respectively. A notable similarity between the black locust and poplar plantations is that harvesting accounts for more than two-thirds of total carbon emissions in both cases.

In timber production in Japan, the final harvesting phase contributes approximately 41-46% of total greenhouse gas (GHG) emissions (Nakano et al. 2018). In Austria, the total greenhouse gas (GHG) emissions from forest timber production were 492,096 tons of CO₂ eq., with harvesting and transportation contributing approximately 14% and 77%, respectively (Kühmaier et al. 2022). Furthermore, Kühmaier et al. (2022) found that the harvesting method using chainsaws resulted in lower greenhouse

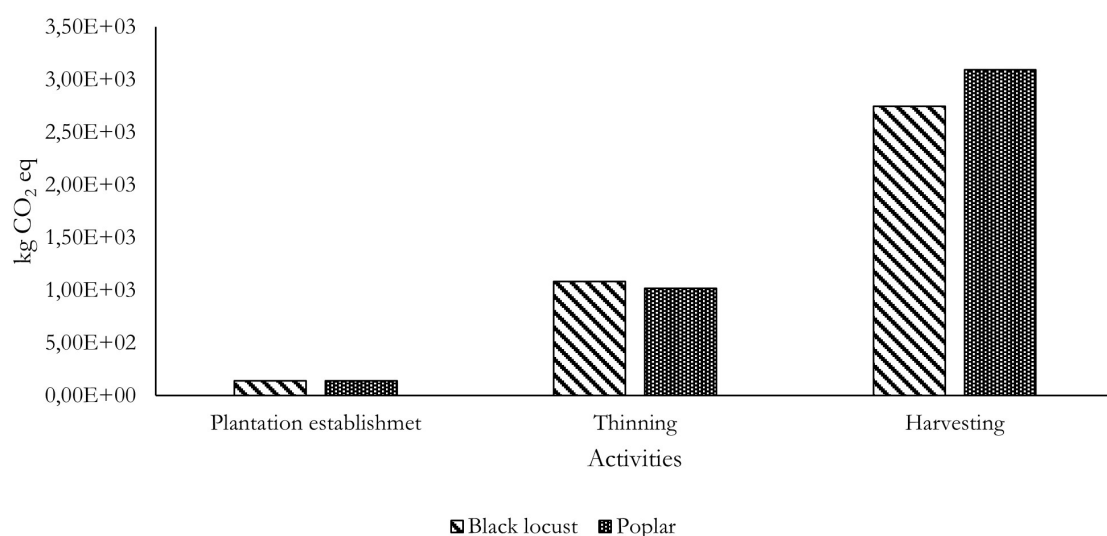


Figure 4. Contribution of the carbon footprint based on activities

gas (GHG) emissions compared to the use of harvesting machinery. Additionally, the distance between forests and industries was identified as contributing to high emissions levels during transportation.

IV. CONCLUSION

Forest operations have caused detrimental environmental impacts from the consumption of energy (fuel and lubricants) and agrochemicals (fertilizers and pesticides). Based on the CML 2001 method, from the ten impact categories, eight impact categories resulted from fuel consumption. Meanwhile, the eutrophication and freshwater aquatic ecotoxicity potential impact categories were primarily caused by fertilizer application.

From the carbon footprint perspective, fuel and lubricant consumption are the main contributors to greenhouse gas emissions. Furthermore, harvesting activity has caused greater environmental impacts than plantation establishment and thinning. Forest operations that use mechanization methods have consumed more fuel and had more detrimental impacts on the environment. The use of machines that emit lower levels of emissions during forest operations is expected to minimize environmental impact.

Based on the findings of this research, minimizing fuel consumption and agrochemical use can reduce detrimental impacts. However, further research should be conducted to elaborate on the equilibrium between optimum timber productivity and low environmental impacts. Due to limitations in the database of life cycle inventory for forest operations in Hungary, we have used relevant information from other Central European countries to assess the environmental impacts of forest operations. Therefore, in the future, each country should develop a database for forestry activities to provide a more accurate database of life cycle inventory.

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