



Carbon footprint and sustainability assessment of wood utilisation in Hungary

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Received: 31 August 2022 / Accepted: 2 July 2023 / Published online: 12 July 2023
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Abstract

Forest management allows the sustained removal of significant amounts of carbon from the atmosphere. Within different activities in the forest, wood utilisation has the most significant man-made environmental impact which affects the carbon balance, which is important to know, to be able to accurately identify its role in climate change. This study aims to determine the carbon footprint of logging during utilisation based on scenario analysis in national default and theoretical assortment structures (11 additional scenarios for each forest stand) within the entire life cycle of raw wood products. Based on a common functional unit (100 m³ of cut wood), a comparative environmental life cycle analysis (LCA) for intermediate and final cutting was performed in shortwood forestry work systems in beech (*Fagus spp.*), oak (*Quercus spp.*), spruce (*Picea spp.*), black locust (*Robinia pseudoacacia*), and hybrid poplar (*Populus x euramericana*) stands in Hungary. After obtaining the results, the present study calculated the carbon footprint order for the utilisation life cycle phases and the entire tree utilisation life cycle. The distribution of absolute carbon footprint (ACF: considered emitted CO₂ from fossil and biotic origins together) by final cutting exhibited the following order: hybrid poplar (6%)—spruce (8%)—beech (26%)—oak (27%)—black locust (33%). The ACF ranking for the whole technological life cycle (intermediate and final cutting, 400 m³ of cut wood) was hybrid poplar—spruce—oak—beech—black locust. The carbon footprint rankings of the studied stands were expanded to the national level.

Keywords Carbon footprint · Wood utilisation · Sustainability assessment · Scenario analysis · Climate change · Hungary

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1 Introduction

Forest ecosystems occupy a substantial part (31%) of the Earth's land surface (UNEP, 2001). Tropical forests cover merely 7% of the Earth's land surface and harbour more than half of the world's species (Wilson, 1988). These forests are highly threatened by human activities (Htun et al., 2011; Manral et al., 2020).

In 2020, the EU had an estimated 159 million hectares of boreal and temperate forests together (forest cover in EU is 39%). Their area has increased by almost 10% since 1990 (145 million hectares) (EUROSTAT, 2021).

Researchers predicted that the clearing of half of the world's residual forests would remove 85% of all the species inhabited by them (Baboo et al., 2017; Fartyal et al., 2022; Kittur et al., 2014). Poverty, population pressure, agricultural expansion and intensification and development of infrastructure have been suggested as major threats to biodiversity (Bargali et al., 2019; Davidar et al., 2010). Due to the above mentioned disturbances, the forests and other land use systems affected adversely in terms of microbial activities, nutrient cycling and reduced the productivity (Karki et al., 2021; Manral et al., 2022; Padalia et al., 2022; Vibhuti et al., 2020).

Hungary's temperate forest area has grown gradually over the past 90 years, thanks to large-scale forest plantings and afforestation. As a result, the forest area of just over 1 million hectares in 1921 now exceeds 2 million hectares. The current forest cover in Hungary is 21% based on the area of forest fragments (Fig. 1). The country wants to increase the forest cover to 27% (NÉBIH, 2021).

Forest management allows for the sustained removal of significant amounts of carbon from the atmosphere (Rumpf et al., 2016). Within different activities in the forest, wood utilisation has the most significant man-made environmental impact which affects the carbon balance, which is important to know, to be able to accurately identify its role in climate change.

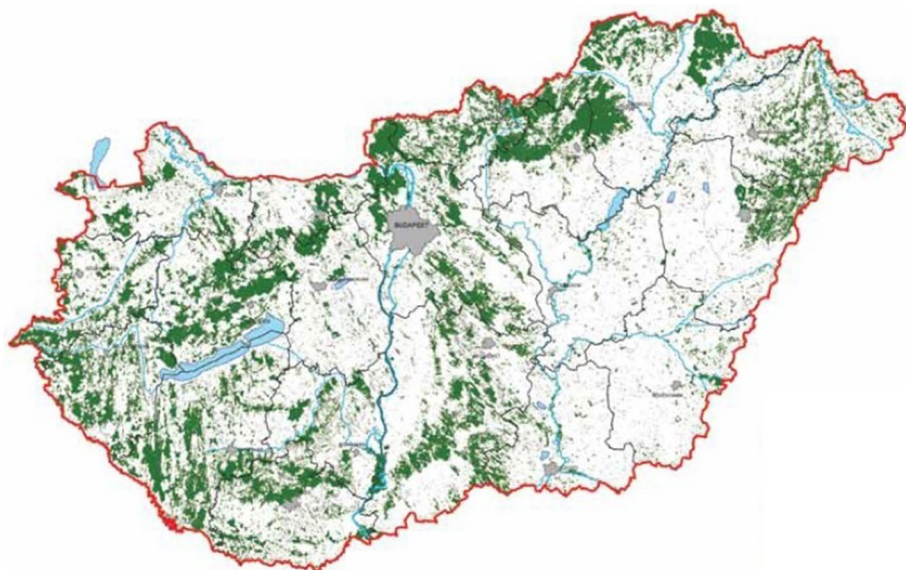


Fig. 1 Forest areas of Hungary (NFK, 2021)

Environmental life cycle assessment (LCA) is an outstanding tool for the well-established analysis of environmental impacts (ISO, 2006a).

The footprint is a quantitative measurement tool expressing the extent of humanity's impact on nature (Hoekstra, 2008), serving as an indicator of the impact on various environmental elements. Carbon footprints indicate air pollution and climate change based on total greenhouse gas (GHG) emissions expressed in terms of carbon dioxide equivalent (Goldfinger et al., 2014). A carbon footprint calculation is based on requirements of international standards (ISO, 2018a, 2018b, 2019). The higher the global warming impact, the larger the carbon footprint of a product, service, activity or technology (Tóthné Szita, 2017). According to Heinimann (2012), we can state that forestry supplies traditional and renewable raw materials and products for various industrial and household processes.

Heinimann (2012) and Klein et al. (2015) reviewed twenty years of LCA forestry practice. Sundberg (1982) and Sundberg and Sanqvist (1987) conducted preliminary energy assessments regarding forest operations. These energy assessments stem from the research of Erkman (1997), Ayres and Kneese (1969), Hall et al. (1979) and Odum et al. (1977). Berg (1995), Karjalainen and Asikainen (1996) and Michelsen et al. (2008) defined forestry mechanisation and fossil fuel need as having a significant environmental impact. Heinimann and Maeda-Inaba (2004) revealed that about two-thirds of the total impact originates from long-distance transportation and forest road infrastructure.

Frühwald and Wegener (1993), Frühwald (1995) and Thoroë and Schweinle (1995) dealt with LCA issues, sustainability, ecological impacts and greenhouse gas (GHG) savings of wood and life cycle modelling in the forestry sector. To develop the forestry application of LCA methodology and to ensure future comparability, Klein et al. (2015) formulated proposals for unification, which complements the ISO specifications 14,040–44:2006 (ISO, 2006a, ISO, 2006b). Their model represents the basis of life cycle assessment in forest production.

Kim et al. (2016) examined the issues of carbon storage in stands of larch and oak. Tellnes et al. (2017) calculated the carbon footprint of wooden products (2017), and Sandin et al. (2016) described it for forestry products.

Many interesting studies on various topics have appeared in the forestry and wood product fields. These include the environmental and socio-economic impacts of wood energy production (Valente et al., 2011), life cycle environmental impacts of firewood (Pierobon et al., 2015; Proto et al., 2017), LCA of bioenergy production (Cherubini et al., 2009) from different wood pellet supply (Sgarbossa et al., 2020), the carbon footprint of forest operations (Cosola et al., 2016), fuel consumption and GHG emissions of forest biomass supply chains (Wihersaari et al., 2005; Jäppinen et al., 2014; Cespi et al., 2014; Murphy et al., 2014; Fuente et al., 2017), environmental impacts of different forest management scenarios (intensive and extensive cases) (González-García et al., 2014), and forestry carbon budget models in life cycle assessment (Head et al., 2019; Somogyi, 2019).

This study highlights the necessity of a carbon footprint calculation in Hungary. The wood utilisation phase is the decisive, connective life cycle stage in the raw wood process chain between the forest production system and the raw wood product processing system. Analysing the wood utilisation phase is a key issue.

The present study aims to calculate, rank and compare the carbon footprint of wood utilisation technologies based on the LCA method (Pierobon et al., 2015) and illustrate this via significant (Rumpf et al., 2016) domestic tree species stands in Hungary (beech, oak, spruce, black locust, hybrid poplar) for intermediate cutting and final harvest; to describe the carbon sequestration capacity of felled wood and examine its possible contribution to climate change (GWP) based on scenario analysis in national

default and theoretical assortment structures to foster a better understanding of the environmental impact of raw wood products.

2 Materials and methods

Hungary is situated between the 45°45'N and 48°35'N latitudes, between 3 climatic zones (oceanic, continental, Mediterranean). For a shorter or longer period of time, any of these types can become prevailing. Due to these reasons, great differences can occur in the weather. The other main determinant is orography. As the country is situated in the Carpathian Basin, more than half of its surface are plains below 200 m, and the area above 400 m is less than 2 per cent. The annual mean temperature in most parts of Hungary is between 10 and 11 °C. In the last century, the climate has warmed in Hungary, as well, it follows the global tendencies, with a greater variability due to being a smaller area. The annual precipitation amount in Hungary is 500–750 mm, but there are remarkable differences between different regions. The country-wide annual precipitation amount showed a decreasing tendency during the last century, the decrease in 109 years was nearly 10 per cent. Due to the location of Hungary the prevailing wind is the northwestern. In Hungary, the southeastern parts have the highest irradiation values (4800–4900 MJ/m²), the global radiation exceeds 4500 MJ/m² in large areas. The lowest irradiation values are around the northern mountains, here less than 4300 MJ/m² values could occur (HMS, 2022).

Applying carbon footprint calculations based on the LCA method (Pierobon et al., 2015) as tool and using the process approach in each case to forestry activities required mapping and selecting specific forestry technologies in the study area (Hungary) as a first step. We identified primary wood production, harvesting, tree utilisation, and wood-processing procedures. With the literature analysis, we stated that tree utilisation activities have the most significant environmental impact; therefore, we focused on the wood utilisation stage in our study, including the intermediate cutting stages and final harvest (in a single-moment approach (Klein et al., 2015)).

Table 1 summarises the amount (m³) of forest wood products by tree species (Table 1) in Hungary in 2017. The most significant contribution was made by the oak, beech, black locust, hybrid poplar and spruce stands (above 10% each, total: 82%). Forest managers sold 6.3 million m³ of forest wood products in 2017, the amount of firewood was 55% and industrial wood 45% (NFK, 2017).

Subsequently, the environmental data mapping of the selected forestry technologies was necessary; this was implemented by the environmental life cycle assessment method (LCA) to determine carbon footprint values.

We followed the requirements of the ISO 14040: 2006 (ISO, 2006a), ISO 14044: 2006 (ISO, 2006b) (No. 1 goal and scope definition; No. 2 life cycle inventory analysis (LCI); No. 3 life cycle impact assessment (LCIA); No. 4 interpretation) and ISO 14067:2018 (ISO, 2018a) (carbon footprint calculation) international standards. We used GaBi Professional software as a tool (GaBi, 2016) for the LCA and carbon footprint calculation and focused on the absolute (ACF: all emitted CO₂, incl. CO₂ from biotic origin), biotic (BCF: emitted CO₂ from biotic origin only) and fossil or technological (FCF: emitted CO₂ from fossil origin only) carbon footprint.

Table 1 Forest wood products by tree species (m³) in Hungary, year: 2017 (NFK, 2017)

Forest wood product	Oak	Beech	Hornbeam	Black locust	Other hardwood	Hybrid poplar	Poplar	Willow	Other softwood	Spruce	Total
Industrial wood (m ³)	299,114	250,189	27,176	243,636	59,460	825,985	189,952	34,978	92,519	839,434	2,862,443
Firewood (above the cutting plate) (m ³)	1,203,254	362,976	177,535	965,254	326,690	76,301	40,744	10,766	150,609	139,938	3,454,067
Total net timber production (above the cutting plate) (m ³)	1,502,368	613,165	204,711	1,208,890	386,150	902,286	230,696	45,744	243,128	979,372	6,316,510

2.1 Goal and scope definition

In characteristic forest stands, we identified and considered versions of the shortwood system with upper landing (beech, oak, black locust, hybrid poplar) and the shortwood (CTL—cut to length) system with upper landing (spruce) as the commonly applied forest management types in Hungary (Rumpf et al., 2016) in our study.

In LCA, in the goal and scope definition step, we explicitly note the reason why we are doing the study, as well as the study reach.

Goal: Our objective was to compare and rank the studied technologies based on their carbon footprint using the LCA method.

According to Pierobon et al. (2015), the *considered system boundaries of wood utilisation technologies regarding examined forest stands were the followings*: The system boundaries determined in wood utilisation technologies (Figs. 2, 3) are as follows: felling area work—conversion landing work—forest and road transport for industrial/public uses—firing of sternwood and branchwood (energy goal)—clearing of felling site.

We also considered the environmental issues connected to production and fuel and lubricating oil use.

Due to a lack of information, the analysis excludes durable wood product production, machine and tool manufacturing dedicated to the studied technologies, the impacts of land use changes and forest road building.

2.2 Wood utilisation processes considered and involved regarding the examined forest stands

The following were considered the technological steps for intermediate cutting and final harvest processes for beech, oak, spruce, black locust, and hybrid poplar stands: felling with motor saw/harvester; delimbing with motor saw/harvester; prebucking with motor saw/harvester; forwarding with forwarder/windless trailer; bucking with motor

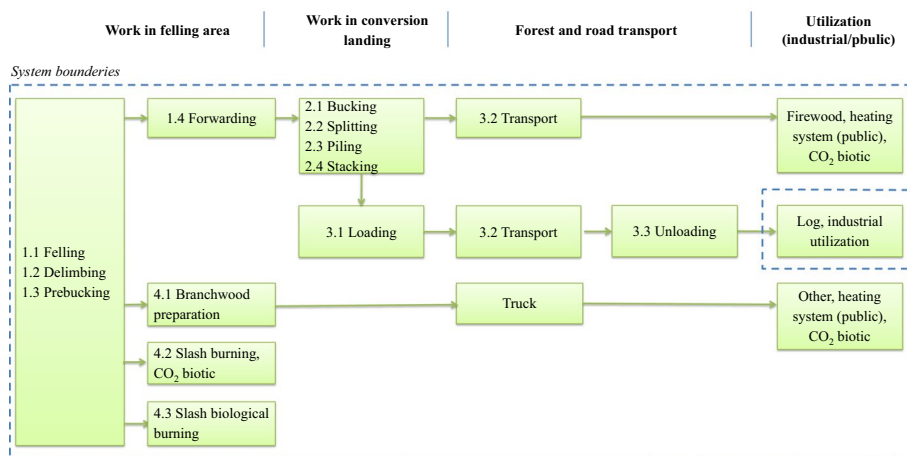


Fig. 2 System boundaries of the shortwood system with upper landing in the final harvest life cycle stage in beech, oak, black locust, and hybrid poplar forest stands in Hungary (Rumpf et al., 2016)

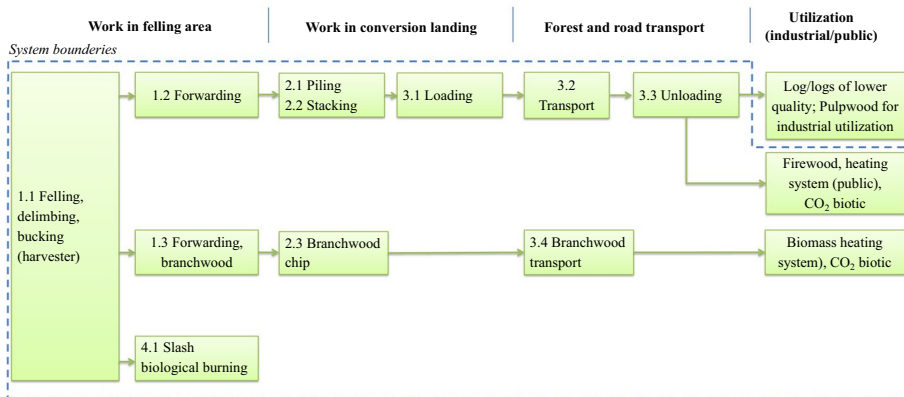


Fig. 3 System boundaries of the shortwood (CTL-cut to length) system with upper landing in the final harvest life cycle stage in spruce forest stands in Hungary (Rumpf et al., 2016)

saw; splitting by hand; piling with forwarder/grabbing trailer; stacking by hand; uploading + transport + unloading with crane truck; firing of sternwood and branchwood (absolute dry, energy goal); burning (semi-humid); and biodegradation of slash.

From a domestic perspective and for practical reasons, the transport distance was uniformly considered as 40 tkm (crane truck) in Hungary (Rumpf et al., 2016).

Table 2 summarises the machine and tool demand (Table 2) in the applied work systems.

The technological steps in beech, oak, black locust, and hybrid poplar stands can be considered equivalent with negligible differences. The main difference in the inventory

Table 2 Examined demand for machines and tools in shortwood systems during final harvest of 1 ha forest stand (Hungary) (Rumpf et al., 2016)

Machines, tools	Unit	Forest Stand	
		Beech, Oak, Black Locust, Hybrid poplar	Spruce
Chainsaw (5 kW)	p	1	1
Forwarder (82 kW)	p	1	1
Truck with crane (RÁBA + LOGLIFT, 10 t bearing capacity)	p	1	1
Harvester (Timberjack 1270B)	p	0	1
Chipper (Jenz Hem 582 built on MAN truck)	p	0	1
Truck (50 kW)	p	1	1
Chariot	p	1	1
Splitting axe	p	1	1
Splitting mallet	p	1	1
Hand hook	p	1	1
Bow saw	p	1	1
Pitchfork	p	1	1
Springloaded measuring tape	p	1	0

data originates from the quantity deviation of the produced standing tree per 1 ha. In the present study, significant differences exist concerning the forestry equipment applied in the spruce stand. The application of the chipper and the harvester appears in the spruce system.

2.3 Functional unit

As a functional unit, 100 m³ of cut wood (Klein et al., 2015) affected by forestry technology was considered according to life cycle stages: life stage 1: cleaning cutting; life stage 2: selection thinning; life stage 3: increment thinning; life stage 4: final harvest. The function of cut wood from a certain area is industrial wood or firewood, but it emerges in different ratio considering each life cycle stages influenced by differing market prices (Table 4).

3 Reference flow

In a quantitative approach, with 100 m³ of cut wood, areas of different sizes (Rumpf et al., 2016) characterise each life cycle stage (ha/100 m³) (Table 3).

3.1 Typical country default assortments considered

Concerning sternwood, firewood, branch firewood, other slash, and wood chips, Table 4 displays the proportion of sternwood/branch firewood and slash as national default values of our study (Rumpf et al., 2016) according to life stages, which clearly illustrates the resulting level of neutral CO₂ (biotic origin from firewood).

In connection with Buzás (2005), we only used the cut wood (above the cutting plate) data of the observation plot to determine the CO₂ sequestration, and therefore, our approach disregarded the organic matter produced by algae, mosses, ferns, herbaceous plants and shrubs in determining the sequestered CO₂ in the forest. We refrained from calculating the amount of CO₂ sequestered by the canopy and roots, implying that the forest sequesters considerably more CO₂ than our calculations indicate. Somogyi (2019) developed the carbon balance modelling of forests based on IPCC methodology in Hungary (CASMOFOR).

Table 3 Areas (ha/100 m³) regarding to life cycle stages of intermediate cutting and final harvest (Rumpf et al., 2016)

Stand	Intermediate cutting			Final harvest
	Stage 1	Stage 2	Stage 3	Stage 4
	CC	ST	IT	FH
	ha/100 m ³ cut wood	ha/100 m ³ cut wood	ha/100 m ³ cut wood	ha/100 m ³ cut wood
Beech	5.00	2.86	1.67	0.91
Oak	6.67	1.59	0.74	0.22
Spruce	6.67	1.67	1.11	0.22
Black locust	10.00	2.00	1.56	0.29
Hybrid poplar	–	–	1.04	0.23

CC Cleaning cutting, ST selection thinning, IT increment thinning, FH final harvest

Table 4 The age (year), felling tree (m³/ha) and firewood (branchwood, thickwood) and harvesting losses (%) as national default values (per 1 ha) (Rumpf et al., 2016)

Stand		Intermediate cutting						Final harvest	
		Stage 1		Stage 2		Stage 3		Stage 4	
		CC		ST		IT		FH	
Beech	Branch firewood %	18 years	37.50	40 years	13.55	75 years	9.50	100 years	8.45
	Other slash %	20 m ³	5.00	35 m ³	2.80	60 m ³	1.60	110 m ³	1.50
	Firewood from sternwood %		82.87		93.85		86.60		55.00
Oak	Branch firewood %	19 years	37.50	35 years	16.00	70 years	10.50	105 years	8.00
	Other slash %	15 m ³	5.00	63 m ³	2.80	135 m ³	1.60	450 m ³	1.50
	Firewood from sternwood %		82.87		74.85		72.50		57.25
Spruce	Branch firewood %	15 years	11.00	29 years	9.50	61 years	9.00	90 years	8.00
	other slash %	15 m ³	5.00	60 m ³	2.80	90 m ³	1.60	450 m ³	1.50
	Firewood from sternwood %		26.00		25.00		24.00		23.00
Black locust	Branch firewood %	6 years	28.00	15 years	17.00	22 years	11.00	35 years	8.00
	Other slash %	10 m ³	1.50	50 m ³	1.50	64 m ³	1.50	341 m ³	1.50
	Firewood from sternwood %		82.87		50.97		81.36		70.02
Hybrid poplar	Branch firewood %		–		–	9 years	14.50	20 years	8.00
	Other slash %	–m ³	–	–m ³	–	96 m ³	1.50	434 m ³	1.50
	Firewood from sternwood %		–		–		7.30		4.38

CC Cleaning cutting, ST selection thinning, IT increment thinning, FH final harvest

3.2 Interpretation of carbon footprint

For carbon footprint interpretation, we followed the concept presented by Polgár et al. (2018), i.e., the carbon storage function of wood products can be included in calculations, which has a significant role in Hungary being able to fulfill the commitments made in the Kyoto Protocol. We calculated the values of the absolute/total carbon footprint (ACF) according to wood utilisation life cycle stages; that is, the fossil/technological carbon footprint (FCF) with fossil CO₂ emissions only and the biotic carbon footprint (BCF) with biogenic CO₂ emissions (from firing absolute dry firewood and semi-humid slash) only.

Assumptions influenced by differing market prices can bring interesting comparisons concerning the utilisation of raw wood products as high-quality timber or as firewood (Führer and Mátyás 2005; Frieden et al., 2012).

3.3 Life cycle inventory analysis

The present study used its own data and expert estimations for the studied technologies (regarding the years of 2013–2016 in Hungary) as primary data (Rumpf et al., 2016). We considered the data from Zala County (South-Western Hungary: beech, oak, spruce stands)

and Nyírség (North-Eastern Hungary: black locust and hybrid poplar stands). We also worked with standard data as secondary data retrieved from the literature and the GaBi Professional database (in particular data concerning the background processes: diesel, lubricating oil and transport); their application was indispensable for the analysis.

3.4 Impact assessment, interpretation

In the standard impact assessment (ISO 14044:2006 (ISO, 2006b)), we first assigned the inventory results to impact categories according to the LCA study aim and frames. The impact categories represent classes of environmental problem areas, which can be assigned to the inventory results. Adhering to Simon (2012), we considered one of the relevant impact categories (Global Warming Potential) of the CML 2001 (Guinée et al., 2002) method as carbon footprint (in an approach of ACF, BCF, FCF). We ranked the life cycle contribution based on the carbon footprint of the studied wood utilisation technologies in different life cycle stages and the whole utilisation technology rotation from an environmental point of view.

Following Polgár et al. (2018), we calculated stand-specific ratios in the next step to normalise the carbon footprint values (ACF, BCF, FCF) to the carbon storage (Buzás, 2005 and Pierobon et al., 2015) of cut wood (Ákos, 1964; Vadász, 1924). We examined all values in terms of 400 m³ of timber, which is the typical amount of cut wood in full technological rotation. We also established nationally extended values based on the quantitative approach values (NÉBIH, 2016).

3.5 Scenario analysis

According to the assumptions influenced by differing market prices, we examined the assortment structure for raw wood product utilisation as high-quality timber or firewood. We performed this by modelling the distribution of industrial wood and firewood as the default at the national level (Rumpf et al., 2016) and theoretically by progressively changing (11 additional scenarios for each forest stand) their proportions by 10–10%. We analysed the ratios representing the carbon sequestration potential in the quantitative approach (400 m³ and extended country level m³ of timber) and assigned them to each a modelled range.

4 Results

The data trends per 100 m³ cut wood reflect the partially different operational steps connected to each technology. Tables 5 and 6 present the aggregated inventory data of the work system typical in the stands, referring to 100 m³ of cut wood.

Based on the CML 2001 (April 2015) method (Guinée et al., 2011), the Global Warming Potential (GWP 100 years) impact category value is the smallest in the final harvest life cycle stage contrary to cleaning cutting since the area-proportional logging of cut wood is the most favourable in the final harvest case (Table 7).

Table 5 Total input and output environmental inventory data of work system in a beech and oak forest stands (Hungary, 2013–2014, winter) (Rumpf et al., 2016)

Parameter	Unit	Stand	Beech (Zala county)				Oak (Zala county)				
			IC				FH	IC			
Stand age	year	18	40	75	100	100	19	35	70	105	
Reference flow: standing wood for cutting	m ³	100	100	100	100	100	100	100	100	100	
Input											
Fuel	kg	46.5	288.3	275.0	337.7	46.0	291.6	277.8	350.3		
Lubricating oil	kg	10.5	55.4	39.3	35.82	10.7	56.1	39.9	37.9		
Output											
CO ₂ emission from fuel	kg	147.5	916.6	872.3	1,068.4	147.3	926.7	880.7	1,108.1		
CO ₂ emission from firewood and slash burning	kg	88,685.0	89,687.4	84,026.5	57,437.6	94,426.0	77,830.8	74,162.1	59,677.2		
Total CO ₂ emission	kg	88,832.5	90,604.0	84,898.7	58,505.8	94,572.7	78,758.3	75,042.7	60,785.3		
Waste oil (recycled)	kg	1.5	24.3	19.7	21.6	1.3	25.1	20.4	23.6		

IC Intermediate cutting, FH Final harvest, S1 Stage 1, S2 Stage 2, S3 Stage 3, S4 Stage 4, CC cleaning cutting, ST selection thinning, IT increment thinning, FH final harvest

Table 6 Total input and output environmental inventory data of work system in a spruce, black locust and hybrid poplar forest stands (Hungary, 2015–2016, winter) (Rumpf et al., 2016)

Parameter	Unit	Stand	Spruce (Zala county)								Black locust (Nyírség)				Hybrid poplar (Nyírség)			
			IC				FH				IC				FH			
			IC	S1	S2	S3	IT	FH	S4	S3	IC	S1	S2	IT	FH	IC	S3	FH
Stand age	year	15	29	61	90	100	100	100	100	100	100	100	100	100	100	100	100	100
Reference flow: standing wood for cutting	m ³	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Input																		
Fuel	kg	46.0	363.5	448.6	433.5	47.0	1050.4	744.4	608.4	636.8	476.6							
Lubricating oil	kg	10.7	44.7	35.3	32.7	10.0	164.4	105.2	120.5	90.2	59.8							
Output																		
CO ₂ emission from fuel	kg	147.3	1,151.2	1,415.7	1,368.2	149.0	3,320.8	2,353.3	1,923.3	2,012.6	1,506.5							
CO ₂ emission from firewood and slash burning	kg	36,218.7	23,385.5	17,912.3	16,927.5	110,675.0	62,484.6	83,814.8	72,635.1	19,001.8	11,475.5							
Total CO ₂ emission	kg	36,365.3	24,536.7	19,328.0	18,295.6	11,0824.0	65,805.4	86,168.1	74,558.4	21,014.4	12,981.9							
Waste oil (recycled)	kg	1.3	25.2	26.6	23.8	1.0	133.4	85.5	63.2	70.6	45.6							

IC Intermediate cutting, FH Final harvest, S1 Stage 1, S2 Stage 2, S3 Stage 3, S4 Stage 4, CC cleaning cutting, ST selection thinning, IT increment thinning, FH final harvest

Table 7 The summarised environmental impacts of wood utilisation life cycle stages in the work systems (beech, oak, spruce, black locust, hybrid poplar stands in total) in each CML 2001 impact category

Impact category, CML 2001 (April 2015)	Unit	Stands			
		IC			FH
		S1	S2	S3	S4
		CC	ST	IT	FH
Global Warming Potential (GWP 100 years)	kg CO ₂ -Equiv	3.31E+05	2.61E+05	2.87E+05	2.24E+05

IC Intermediate cutting, *FH* Final harvest, *S1* Stage 1, *S2* Stage 2, *S3* Stage 3, *S4* Stage 4, *CC* cleaning cutting, *ST* selection thinning, *IT* increment thinning, *FH* final harvest

4.1 Carbon footprint calculation. Technology ranking, impact rating of technologies

The ranking of the work systems in the final harvest life stage in a quantitative approach based on 100 m³ of cut wood is as follows: the absolute carbon footprint (ACF) of hybrid poplar (6%) and spruce (8%) stands were the smallest, while beech (26%), oak (27%) and black locust (33%) stands still showed a significant contribution. We also experienced similar values in the increment thinning life stage.

The total carbon footprint development regarding the whole life cycle among the examined system boundaries, namely the total wood utilisation technological rotation, was examined.

In a quantitative approach, based on 400 m³ of cut wood, the total carbon footprint (total ACF) ranking is hybrid poplar (68,404.0)—spruce (98,847.0)—oak (309,009.0)—beech (323,600.0)—black locust (337,651.0) (in the values of GWP 100 years [kg CO₂-Equiv.]).

Table 8 illustrates the rankings below.

Based on the NÉBIH (2016) logging data release, the national carbon footprint (national ACF) ranking of the studied stands was expanded to the national level with the following ranking: hybrid poplar (122,138,751)—spruce (196,313,384)—oak (364,095,882)—beech (372,903,672)—black locust (1,053,723,566) (in the values of GWP 100 years [kg CO₂-Equiv.]).

The CO₂ emission values resulting from the burning and biological burning of firewood (abs. dry) and slash (semi-humid) (BCF) offer a nuanced understanding of the contribution of technological processes (FCF).

CO₂ emissions of biotic origin resulting from wood firing (BCF) have a major influence (88–98%) on the absolute carbon footprint (ACF) of the total life cycle. Moreover, the same stand ranking appears in both cases (ACF and BCF).

However, in the fossil carbon footprint of technological processes (FCF), the differences arise from the technology and mechanisation solutions (degree of mechanisation) and the biological and physical features of stands per ha (e.g. forest stand density per ha, quantity and weight of standing wood before cutting, density, and wood moisture).

Within the stands, the contribution of the fossil carbon footprint of technological processes (FCF) relative to the carbon footprint of biotic origin (BCF) is the smallest in beech, oak and black locust (1–3%), while it is larger in spruce and hybrid poplar stands (9–12%).

Table 8 The ratio and ranking of life cycle impact contribution of technologies according to the carbon footprint of utilisation (absolute, including biotic CO₂)

IC	FH				Total			
	S2		S3		S4		FH	
CC	ST		IT		FH		FH	
Stand ranking (100 m ³)	CF	%	Stand ranking (100 m ³)	CF	%	Stand ranking (100 m ³)	CF	%
Spruce	36,400	11	Spruce	24,700	9	Spruce	19,476	7
Beech	88,900	27	Black locust	66,300	25	Hybrid poplar	21,143	7
Oak	94,600	29	Oak	79,000	30	Oak	75,091	26
Black locust	111,000	33	Beech	90,800	36	Beech	85,200	30
—	—	—	—	—	—	Black locust	86,319	30

CF—carbon footprint (ACF, absolute, incl. biotic CO₂) CML2001—Apr. 2015, Global Warming Potential (GWP 100 years) [kg CO₂-Equiv.]; %—Stand life cycle contribution in the examined life stage [%]; Total—Total CF [kg CO₂-Equiv.]

IC Intermediate cutting, FH Final harvest, SI Stage 1, S2 Stage 2, S3 Stage 3, S4 Stage 4, CC cleaning cutting, ST selection thinning, IT increment thinning, FH final harvest

In a quantitative approach, based on 100 m³ of cut wood, the ranking of fossil carbon footprint (FCF) is oak (2912.89)—beech (3763.53)—spruce (4403.01)—hybrid poplar (7449.54)—black locust (8,041.48) (in the values of GWP 100 years [kg CO₂-Equiv.]).

Based on the NÉBIH (2016) logging data release, the fossil carbon footprint (national FCF) ranking of the studied stands was expanded to a national level with the following ranking: oak (4,070,675.69)—beech (6,760,703.69)—spruce (13,406,635.16)—hybrid poplar (14,629,341.83)—black locust (22,586,567.7) (in the values of GWP 100 years [kg CO₂-Equiv.]).

We found that work in the felling area caused 30–40% of fossil CO₂ emissions; uploading, transport, and unloading of wood caused 60–70%.

4.2 Carbon footprint vs. carbon sequestration

Table 9 presents the stand ratio specific ratio (Polgár et al., 2018) regarding carbon sequestration potential in a quantitative approach based on 400 m³ of cut wood to the whole technology rotation at the national level based on the NÉBIH (2016) logging data release.

In the quantitative approaches (based on 400 m³ of cut wood and the national level according to the NÉBIH (2016) logging data release, in the case of the carbon footprint characteristic of the whole technology (absolute carbon footprint, ACF and the burning of firewood and slash and the biological combustion of slash (biotic carbon footprint, BCF dimension), the ratios are between 1.60–4.90 and 1.62–5.50 and 1.78–6.23 and 1.82–7.08. For the carbon footprint of technological processes (fossil carbon footprint, FCF dimension): the ratios are between 44.97–178.49 and 52.02–161.33.

The ratio values indicate positive carbon sequestration potential, system sustainability and the order of magnitude experienced in the absolute carbon footprint (ACF) value and per biotic (BCF) and fossil dimension (FCF) within the system boundaries of the wood utilisation life stage concerning the national default values of industrial wood and firewood distribution.

5 Discussion

5.1 Scenario analysis

Outcomes of the research are comparable with other LCA studies only in the case of the same functional unit and system boundaries. However, studying relevant literature we can state congruency between different research results regarding carbon footprint (González-García et al., 2014; Pierobon et al., 2015).

Forest management allows for the sustained removal of significant amounts of carbon from the atmosphere (Cherubini et al., 2009; Klein et al., 2015); within this, the different utilisation of the produced wood (FCF in our case) significantly affects these processes (Berg, 1997; Heinimann, 2012; Karjalainen & Asikainen, 1996; Michelsen et al., 2008; Solli et al., 2009).

As a result of this study, we found that work in the felling area caused 30–40% of fossil CO₂ emissions; uploading, transport, and unloading of wood caused 60–70%. The same results were found by Heinimann and Maeda-Inaba (2004), Cherubini (2010), Murphy et al. (2014) and Pierobon et al. (2015).

Table 9 Carbon footprint vs. carbon sequestration, a developed specific ratio of forest stands regarding to carbon sequestration potential

Approach	Stand	Standing wood for cutting	CO ₂ need/Whole technology CF	CO ₂ need/Burning CF	CO ₂ need/Technological processes CF
Quantitative (based on 400 m ³ of cut wood)	Hybrid poplar	400	4.90	5.50	44.97
	Spruce	400	3.12	3.27	70.12
	Oak	400	1.68	1.70	178.49
	Beech	400	1.60	1.62	137.38
	Black locust	400	1.60	1.64	67.19
Quantitative national level (based on NÉBIH (2016) logging data release)	Hybrid poplar	908,733	6.23	7.08	52.02
	Spruce	994,015	3.91	4.19	57.23
	Oak	505,244	1.80	1.82	161.33
	Beech	557,642	1.93	1.97	106.61
	Black locust	1,391,860	1.78	1.82	83.24

CF—Carbon footprint; Whole technology CF—Whole technology rotation carbon footprint, ACF [kg CO₂-Equiv.]; Burning CF—Fire wood and slash burning (incl. biological) carbon footprint, BCF [kg CO₂-Equiv.]; Technological processes CF—Technological processes carbon footprint, FCF [kg CO₂-Equiv.]; Standing wood for cutting—Standing wood for cutting in the whole technology rotation [m³]; CO₂ need—CO₂ need from the atmosphere sequestered by the stand (cut wood) necessary for the carbon storage of the given tree species [kg CO₂]; CO₂ need / Whole technology CF—CO₂ need of stand (cut wood) [kg] / Whole technology rotation carbon footprint, ACF [kg CO₂-Equiv.]; CO₂ need / Burning CF—CO₂ need of stand (cut wood) [kg] / Burning and biological burning of firewood and slash carbon footprint, BCF [kg CO₂-Equiv.]; CO₂ need / Technological processes CF—CO₂ need of stand (cut wood) [kg] / Technological processes carbon footprint, FCF [kg CO₂-Equiv.]

Wood could substitute more energy intensive materials with higher GHG-burdened footprints during their production and end-of-life stages (Frühwald & Wegener, 1993). Additionally, emissions from fossil resources could be avoided when wood is burned (BCF in our case) at the end of its life cycle (Cespi et al., 2014; Cherubini et al., 2009; Pierobon et al., 2015). Nilsson et al. (2011) found that forest management can play an important role in the mitigation of climate change.

According to the assumptions influenced by differing market prices and the possible climate change effects currently and in the future (Frühwald & Wegener, 1993), we examined the assortment structure for raw wood product utilisation as high-quality timber or firewood (Führer and Mátyás 2005; Frieden et al., 2012). In the following, we demonstrate the ratio values expressing the carbon sequestration potential of the changing distribution of industrial wood and firewood by stands, according to 400 m³ cut wood for the whole technological rotation. The red bar in the figure below (Figs. 4, 5, 6, 7, 8) indicates the starting national default assortment plot structure as a baseline option. The remaining bars indicate the 10–10% changes in the proportions between 100% industrial wood and 100% firewood as the extremes.

The figures (Figs. 4, 5, 6, 7, 8) illustrate the significant difference between the ratio value representing high carbon sequestration potential in the theoretical 100% ratio of industrial wood (0% firewood) and the value in the minimal firewood proportion (approx. 10%). The difference results from the carbon footprint of technological processes (FCF) of whole rotation tree utilisation activities for 400 m³ (which, in the '100% industrial wood case, assuming durable carbon sequestration, equals the full carbon footprint (ACF) of the system) is only 4–12% of the carbon footprint (ACF) characterising the whole system occurring in the approx. 10% firewood range. With the approx. 90% theoretical utilisation of harvested timber as firewood for energetic purposes, the carbon footprint of technological processes (FCF) occurs only as a 1–2% proportion in the whole system. Results in this study are coherent with the outcomes of Pierobon et al. (2015), where the firewood supply chain were mentioned carbon neutral because of the absorption of CO₂ of biomass, which offsets the emissions regarding fossil dimension of the carbon footprint (FCF).

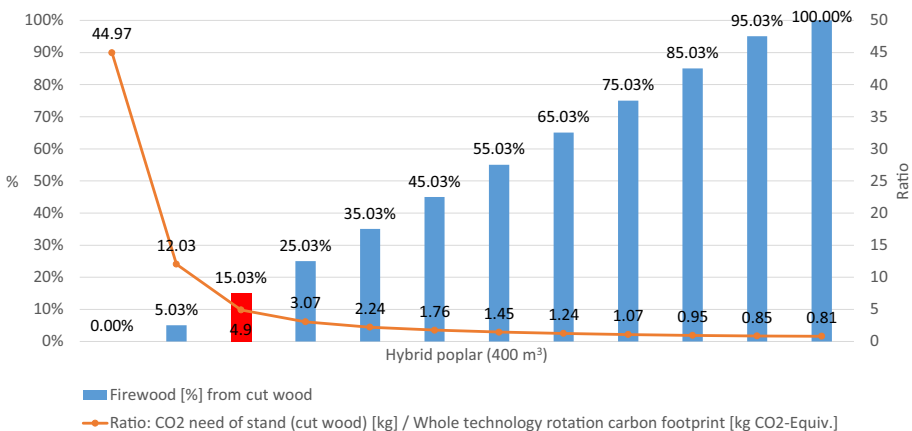


Fig. 4 Absolute carbon footprint (ACF) vs. carbon sequestration ratios. Hybrid poplar stand (400 m³). Ratio values expressing the carbon sequestration potential assigned to the change of the distribution of industrial wood and firewood

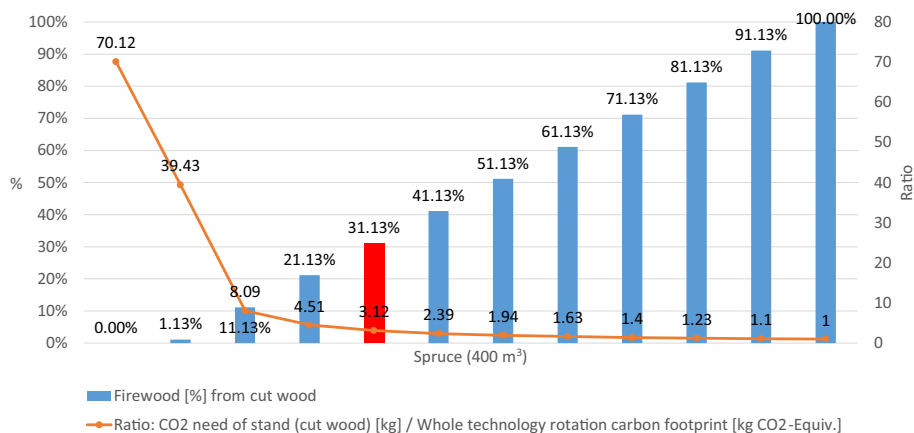


Fig. 5 Absolute carbon footprint (ACF) vs. carbon sequestration ratios. Spruce stand (400 m³). Ratio values expressing the carbon sequestration potential assigned to the change of the distribution of industrial wood and firewood

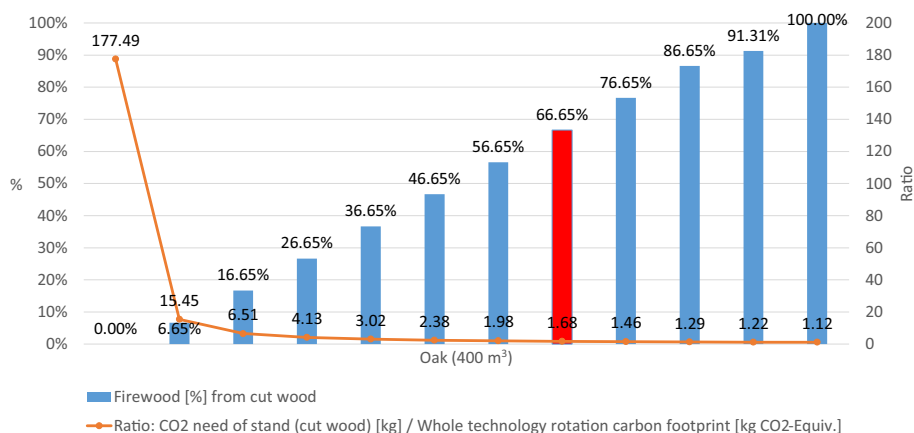


Fig. 6 Absolute carbon footprint (ACF) vs. carbon sequestration ratios. Oak stand (400 m³). Ratio values expressing the carbon sequestration potential assigned to the change of the distribution of industrial wood and firewood

Our estimate verifies the statement of Klein et al. (2015) at the forest production stage of the raw wood process chain, according to which wood is a low-emission raw material. Based on the environmental impacts studied at the wood utilisation stage, the positive carbon sequestration potential of the forest production stage can be premised relative to the ratios. This pertains particularly to our research because we interpreted the carbon sequestration of the above-ground biomass specifically only for cut wood, implying that the forest sequesters considerably more CO₂ than our calculation represents. Our research outcomes are similar to the results of (Frühwald & Wegener, 1993), Góralczyk (2003), Cherubini et al. (2009) and Lippke (2011), where the advantages of replacing fossil fuels with wood were proven.

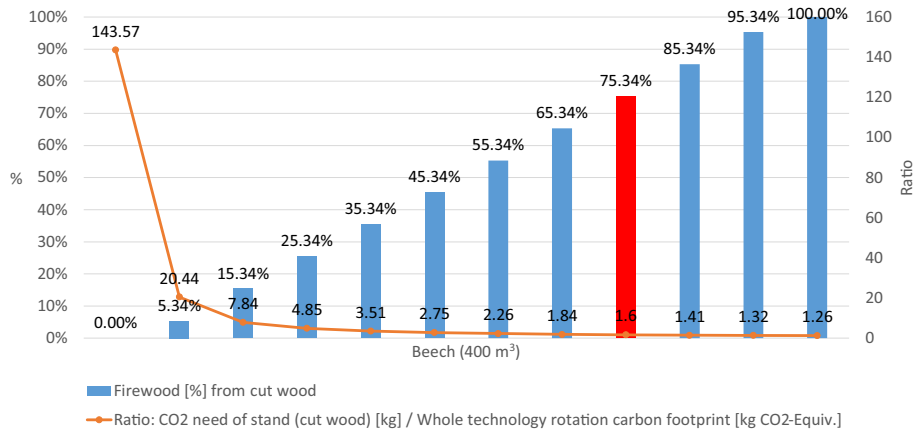


Fig. 7 Absolute carbon footprint (ACF) vs. carbon sequestration ratios. Beech stand (400 m³). Ratio values expressing the carbon sequestration potential assigned to the change of the distribution of industrial wood and firewood

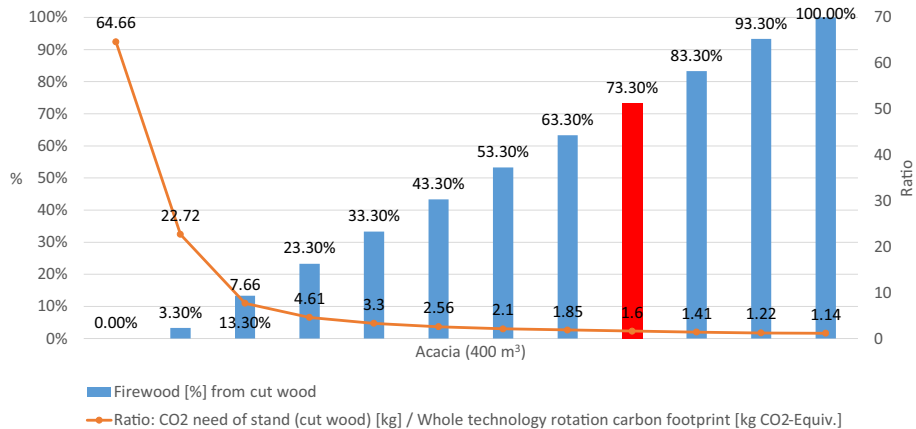


Fig. 8 Absolute carbon footprint (ACF) vs. carbon sequestration ratios. Black locust stand (400 m³). Ratio values expressing the carbon sequestration potential assigned to the change of the distribution of industrial wood and firewood

5.2 Environmental risk in relation to climate change

The carbon footprint-based range of the presented technological processes quantitates their contribution to the increase in global warming.

However, further studies should also consider the probability that spruce and beech distribution areas could decrease dramatically (Móricz et al., 2013) in Hungary due to increasing temperatures and decreasing summer precipitation (Gálos et al., 2015) toward the end of the twenty-first century. A decision support system in forestry that offers suggestions concerning climate-resilient tree species (Czimer & Gálos, 2016; Mátyás et al., 2018) is currently being developed for Hungary. According to this, if tree species policies change and the planting of other tree species (e.g. oak) is promoted in the area of the current spruce and beech stands, the technological processes connected to these species will

change the total environmental risk of the forest technologies in Hungary; that is, its contribution to increasing the concentration of atmospheric greenhouse gases.

Currently, in European terms, there is no other country with such a climate as Hungary. There may be similar temperature and precipitation conditions elsewhere in one season, but similar throughout the year is so difficult to find. This unique climate also comes from the nature of the Carpathian Basin (Führer and Mátyás, 2005). Thus, the results of the study can theoretically be used by those countries with the same climate as Hungary, or those with the same climate in the future as Hungary currently has, e.g. expected to be certain areas of Germany and Poland. Furthermore, those where the same degree of temperature and precipitation changes are expected, but only if the forest stands are similar (Gálos et al., 2015).

Considering the Hungarian aspects Illés and Móricz (2022) concluded that, according to the optimistic scenario, by the end of this century, the spatial extent of suitable areas for oak species may drop to one fifth of the value measured at the turn of the 2000s. The only exception is downy oak, whose suitable area can multiply at the expense of other oak species. Another species on the losing side is beech whose climatically suitable area can reduce to one tenth of its former value. Beside the above, black pine can gain more and more areas. According to the models, the extent of the areas for which it will probably not be possible to find climate analogue provenances in Europe increases by orders of magnitude (Illés & Móricz, 2022).

6 Conclusions

The present study performed the comparative carbon footprint calculation based on the LCA method for intermediate cutting (cleaning cutting, selection thinning, increment thinning) and final harvesting in beech, oak, spruce, black locust, and hybrid poplar stands in Hungary (functional unit: 100 m³ of cut wood).

We found that CO₂ emissions of biotic origin (BCF) resulting from wood firing have a major influence on the absolute carbon footprint (ACF) of the total life cycle (88–98%). In the fossil carbon footprint of technological processes (FCF), the differences arise from the technology and mechanisation solutions (degree of mechanisation) and the biological and physical features of stands per ha (e.g. forest stand density per ha, quantity and weight of standing wood before cutting, density, and wood moisture of wood).

We examined the carbon footprint values in a whole technology rotation (400 m³ of cut wood) and a national extension. Based on 400 m³ of cut wood, the total carbon footprint (total ACF) ranking is hybrid poplar (68,404.0)—spruce (98,847.0)—oak (309,009.0)—beech (323,600.0)—black locust (337,651.0) (in the values of [kg CO₂-Equiv.]).

Stand-specific ratio (Polgár et al., 2018) values were good indicators of the multiple, positive carbon sequestration potential and capacity and system sustainability.

According to the assumptions influenced by differing market prices, we examined the assortment structure for raw wood product utilisation as high-quality timber or firewood. We analysed the ratios representing the carbon sequestration potential (400 m³ and extended country level m³ of timber) and assigned them to each modelled range. Knowledge of the carbon footprint (ACF, BCF, FCF) of wood utilisation processes and the carbon storage of cut wood strongly influences the consideration of raw wood products as low-emission raw materials (Klein et al., 2015). This information helps more accurately identify the role of technologies in climate change, climate risks and sustainability issues.

Acknowledgements This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme. We thank Dr Katalin Mátyás Szakálosné, Dr Attila László Horváth, Prof. Dr János Rumpf and Dr Veronika Fodor Elekné for their valuable comments and expert data concerning wood utilisation processes in Hungary.

Funding Open access funding provided by University of Sopron.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Consent for publication The authors declare that the manuscript is their own original work that not published in other Journal earlier and consent to its publication.

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