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Ecological Footprint of Wood-Based Products in the Ukrainian Carpathians Region

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In Ukraine's Carpathian region, the absence of research on the ecological footprint (EF) of wood products poses challenges amidst unsustainable forestry practices, climate change, and human impacts that threaten forest ecosystems and local communities. This study addresses this gap by assessing and comparing the EF of furniture boards and solid structural timber produced by two wood-processing enterprises in the Carpathians. Using the ecological footprint of production methodology based on life cycle assessment, it calculates the cumulative environmental impacts of production, use, and disposal of these products, applying global productivity and equivalency coefficients. The analysis distinguishes between direct and indirect EFs: direct EF covers land use for forest resources and other areas, while indirect EF considers the land required to absorb CO_2 emissions from production. The findings reveal that the total EF for producing 1 m^3 of furniture boards at enterprise "A" requires 0.475 ha, while structural timber at enterprise "B" needs only 0.111 ha, underscoring the different environmental impacts. A primary contributor to the EF is heat energy for drying lumber, generated by burning wood waste. Offsetting CO_2 emissions from this process requires 0.353 ha/m^3 of land for furniture boards and 0.088 ha/m^3 for structural timber. Additionally, electricity consumption for machinery adds 0.081 ha/m^3 for furniture boards and 0.011 ha/m^3 for structural timber. Transport emissions further increase the EF, with 0.026 ha/m^3 required for furniture boards and 0.002 ha/m^3 for structural timber. These results highlight the need for enhanced resource efficiency to mitigate environmental impacts, particularly in heat generation and transportation.

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Introduction

Forest ecosystems occupy a substantial part (15.9%) of Ukraine's land area [Poliakova and Abruscato 2022]. Forest areas are distributed very unequally within the country; the forest cover is greatest in northern Polissya (26.8%) and the Ukrainian Carpathians (42%), and local communities there are economically and socio-culturally highly dependent on forest resources [Chernyavskyy et al. 2011; Henyk et al. 2011; Melnykovych and Soloviy 2014]. An important element in their daily life is the collection of non-wood forest products – mushrooms, berries, nuts, medicinal plants, bark, roots, juice, and resin [Golubets et al., 2007; Osadchuk et al., 2018] – which are essential for subsistence (in supplementing diets) and as a source of additional

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household income [Stryamets et al, 2011, Zhyla et al, 2018]. A high unemployment rate and a low level of income per capita, especially in the mountain regions of Ukraine, force local stakeholders to adopt unsustainable forest practices [Melnykovych and Soloviy 2014]. In the Ukrainian Carpathians, changing climatic conditions and mounting pressure from human activities are causing forests to lose their productivity, vitality, and resilience against destructive abiotic and biotic impacts [Stoyko 1998]. These changes undermine the well-being of local communities and the prosperity of this entire fragile mountain region [Krynytskyy and Chernyavskyy 2014; Melnykovych and Soloviy 2014; Soloviy and Chernyavsky 2011]. Currently, first of all because of war [Lloyd et al, 2023], and also due to low income in rural areas, due to military actions, poverty, population pressure, agricultural expansion and intensification and development of infrastructure, Ukraine is losing its forests and other valuable ecosystems, and is seeing its biodiversity put under pressure.

The Ecological Footprint (EF) stands as a quantitative tool measuring humanity's impact on nature, serving as an indicator for the environmental consequences of various activities [Hoekstra 2008]. Introduced in the early 1990s by Wackernagel and Rees [1996], the EF model tracks human demand on regenerative and waste absorptive capacity within the biosphere, covering categories such as cropland, grazing land, fishing ground, forest land, built-up land, and carbon uptake land. More than a mere assessment indicator, the EF has become a crucial metric for over 20 countries in gauging various aspects of sustainable development [Niccolucci et al. 2008; Cerutti et al. 2010; Herva et al. 2012b].

The EF methodology, distinguished from Life Cycle Assessment (LCA), provides a comprehensive index that amalgamates contributions from diverse flows, expressed in globally understandable units of global hectares (ha) [Chomkhamsri and Pelletier 2011]. Its suitability for industries with high natural resource demands, such as the wood-based panels industry, stems from its ability to measure the biologically productive land and sea area used by a given population or activity based on prevailing technology and resource management schemes [Kitzes and Wackernagel 2009; Chambers and Lewis 2001]. Despite some limitations, such as not encompassing certain emissions and the challenge of summarizing different land categories into a single number, EF analysis remains a valuable tool for sustainability assessments, providing insights into consumption patterns and environmental consequences at various levels, from individuals to countries and the global population [Chambers et al. 2000].

Based on U.S. Forest Service data [Palmer 1998], the annual U.S. demand for wood products requires about 0.04 acres of forest per person. Wernich et al. [1998] further note that it takes 40 to 70 years to restore an acre of forest after harvesting. To sustain our current consumption, a minimum of 40 times 0.04 acres per capita is needed, resulting in a wood product footprint of 1.60 acres. Earth has approximately 10.13 billion acres of forest [Brown et al. 1996], and a global population of 10 billion consuming wood products as at present would require 16 billion acres for sustainability if all forests were dedicated to human use. The diminishing quality and quantity of Earth's forests challenge this sustainability condition, suggesting the need for potential cutbacks in wood product use or alterations in forest management in the coming decades.

Numerous compelling studies within the forestry and wood product domains have explored a diverse range of topics, particularly concerning ecological footprint and life cycle assessments. For instance, researchers have looked at the environmental and socio-economic impacts of wood energy production [Valente et al. 2011]. They have also scrutinized the life cycle environmental impacts associated with firewood [Pierobon et al. 2015; Proto et al. 2017]. Moreover, life cycle assessments (LCAs) of bioenergy production, as studied by Cherubini et al. [2009], have been conducted across various wood pellet supply chains, as exemplified by the work of Sgarbossa et al. [2020].

In addition, significant attention has been given to understanding the carbon footprint of forest operations, as highlighted in research by Cosola et al. [2016]. Fuel consumption and greenhouse gas emissions within forest biomass supply chains have been thoroughly examined in various studies [Wihersaari et al. 2005; Jäppinen et al. 2014; Cespi et al. 2014; Murphy et al. 2014; de la Fuente et al. 2017].

Exploring the EF for cities with a focus on wood fuel consumption, Abd'Razack and bin Muhamad Ludin [2013] report that in both urban and rural Africa, the primary source of energy is wood fuel, causing devastating impacts on forests and ecosystems. Those authors demonstrated that the depletion of forests leads to substantial emission of CO_2 into the atmosphere, highlighting the detrimental effects of deforestation. Furthermore, Polgár [2023] performed a comparative carbon footprint calculation based on the LCA method specifically for logging. This research sheds light on the environmental consequences of logging activities, providing valuable insights for understanding and mitigating the environmental impacts associated with wood fuel consumption and logging practices.

Researchers have not only scrutinized these specific aspects, but have also explored broader themes. Environmental impacts stemming from different forest management scenarios, including both intensive and extensive cases, have been studied [González-García et al. 2014]. Additionally, models for forestry carbon budgets in life cycle assessments have been developed and explored by researchers such as Head et al. [2019]. Integrating these studies, the wealth of research reflects the multifaceted nature of investigations within the forestry and wood product fields. Adding to this body of knowledge, research by Nie et al. [2010] on the EF of Chinese log imports provides a nuanced perspective, suggesting that despite China's significant role as a timber importer, the ecological impact on global forest resources may not be as dangerous as previously thought. This wealth of research reflects the multifaceted nature of studies within the forestry and wood product fields.

Ongoing research, involving continuous refinement and enhancement of the EF methodology [Huijbregts et al. 2008; Siche et al. 2008, 2010; Herva et al. 2010, 2012b], has expanded its initial focus on natural resources accounting to include the assessment of production systems [Niccolucci et al. 2008; Cerutti et al. 2010; Herva et al. 2012b]. Various studies in the literature have explored EF applications in specific product or production processes, spanning the food sector [Niccolucci et al. 2008; Mamouni et al. 2009; Cerutti et al. 2010; Herva et al. 2012a], the textile sector [Herva et al. 2008; Herva et al. 2011], electronics [Frey et al. 2006], construction materials [Herva et al. 2012b] and utilities [Lenzen et al. 2003]. Notably, there is a dearth of prior research on the application of EF methodology to assess the EF of wood products, although there exist studies relating to wood and non-wood pulp [Kissinger et al. 2007], particleboard [Saravia-Cortez et al. 2013], and wood pallets [Alvarez and Rubio 2015]. The absence of similar studies in Ukraine represents a research gap in evaluating the EF of wood products within the Ukrainian context [Pelyukh et al. 2023]. This underscores the significance of our present study in contributing valuable insights into the EF of wood products in the Ukrainian Carpathians region.

By focusing on two wood-processing enterprises in the Ukrainian Carpathians region, the research aims to provide a comprehensive assessment, ranking, and comparison of the EF of wood products (furniture boards and solid structural timber), offering valuable insights for sustainable development and forest management practices in this ecologically sensitive region. Ultimately, the findings aim to contribute to informed decision-making for the conservation and responsible management of the Ukrainian Carpathians' invaluable natural resources.

Materials and methods

Study area

Both studied enterprises are situated in the Ukrainian Carpathians region, where they implement typical production and technological processes characteristic of wood-processing enterprises throughout Ukraine. These enterprises specialize in producing goods that reflect modern trends in wood utilization, resource-efficient management, and the application of zero-waste production principles.

Wood-processing enterprise "A" is located in western Ukraine, in the Lviv region, and primarily specializes in the production of hardwood furniture boards. The enterprise's installed production capacity allows it to produce over 200 m^3 of furniture boards per month, with a total workforce of 130 industrial and production personnel. Responding to modern trends in zero-waste production and the development of alternative energy sources, since 2020 the enterprise has been producing fuel briquettes and pellets. These fuel products are derived from the company's own production waste, such as shavings and sawdust, enabling a reduction in environmental impact and promoting more efficient resource use.

Wood-processing enterprise "B", located in the Ivano-Frankivsk region in western Ukraine, specializes in the production of modern wooden construction materials, frame buildings, and structures. The enterprise's installed capacity allows for the processing of up to 18,000 m^3 of round timber annually, with a total workforce of 50 industrial and production personnel. Production waste not utilized for heat generation is sold for the manufacture of board materials, aligning with the principles of environmental sustainability and efficient resource utilization.

These two wood-processing enterprises, producing furniture boards and structural timber, represent typical examples of organizations within Ukraine's Carpathian wood-processing sector. Their production processes, based on modern principles of waste management and sustainability, form the basis for analyzing the EF of wood products, which is the goal of this study. The results obtained will support informed decision-making for the conservation and responsible utilization of the valuable natural resources of the Ukrainian Carpathians.

Methods

The Ecological Footprint of a Product (EFP) determines the necessary resource demand on the environment through the product, service or activity. The proposed unit of EFP is the global ha year [Global Footprint Network 2009]. EFP is calculated as the sum of the impacts of all n-actions required for the creation, use, and disposal of product P, in accordance with the LCA approach [Global Footprint Network 2009; Niccolucci et al. 2008]. In general, the equation for calculating EFP will be as follows:

$$EFP = \sum_{i=1}^{n}\sum_{j=1}^{6} EFP_{i,j} \tag{1}$$

where i enumerates the inventoried objects participating in the P production chain, and j the six different types of land considered, namely cropland, forests, fishing grounds, pastures, land for carbon sequestration, and built-up land.

The calculation of the EFP for each single input element i is carried out according to equation (2):

$$EFP_i = \sum_{j=1}^{6} A_j \times YF_j \times EQF_j \tag{2}$$

The sum for the different land types can be obtained by transforming ha (A) into global ha (i.e., ha with average world productivity) using equivalence factors (EQF) and yield factors (YF) [Global Footprint Network 2009; Wackernagel and Rees 1996]. These are factors of scaling based on land productivity. Specifically, EQF_j converts a specific land type j (e.g., cropland) into a universal unit of biologically productive area (namely, the global ha), while YF accounts for the difference between national and global productivity indicators for that specific land type [Galli et al. 2007]. The meaning of the factors is based on the indices of agricultural suitability from the Global Agro-Ecological Zone (GAEZ) model [FAO 2000]. After conversion, average global ha represent ha with the average global productivity of all considered land types, i.e., global ha. The YF and EQF factors for all land types and countries for a specific year are calculated and provided by the Global Footprint Network (GFN) on an annual basis [Global Footprint Network 2024].

In addition, special conversion factors are needed for data that is not directly expressed in the area:

– if the input data are expressed in mass units (M, t/year), they can be converted into area units (A) using the land use efficiency conversion factor (Y) specific to the product, region and season (equation (3)) [Galli et al. 2007]:

$$\mathrm{A}_i = \frac{\mathrm{M}_i}{Y_i} \tag{3}$$

– if the data are expressed in terms of carbon dioxide equivalents, they can be converted to global ha using equation (4):

$$\mathrm{A}_{i\ Forest} = \frac{CDE_i}{AFCS} \tag{4}$$

where CDE_i is the equivalent emission of carbon dioxide specific to pollutant type i (t of CO_2), and AFCS (Average Forest Carbon Sequestration) is the long-term ability of one ha of the world-average forest ecosystem to absorb atmospheric carbon dioxide through the photosynthesis mechanism – this was recently updated to 0.73 $\frac{tons_{\mathrm{C}}}{ha \times year}$ or 2.67 $\frac{tons_{CO_2}}{ha \times year}$ [Mancini et al. 2016].

As a result of human activities, a large number of harmful substances are formed, including greenhouse gases. In addition to carbon dioxide (CO_2), these include water vapor (H_2O), nitrogen oxide (N_2O), methane (CH_4), ozone (O_3), sulfur hexafluoride (SF_6), hydrofluorocarbons and perfluorocarbons. For comparison and consolidation into a single measure, greenhouse gas emissions were converted to carbon dioxide equivalent. Equation (5) is used for this purpose.

$$CDE_i = M_i \times \mathrm{E}_{\mathrm{CO}_2}, \mathrm{t} \tag{5}$$

where denotes emissions of greenhouse gas type i (t), and is the global warming potential of the greenhouse gas. When determining the EFP, the global warming potential of greenhouse gases was considered over a century-long period.

Overall, the total EFP can be divided into two components, labeled as direct (DIR) and indirect (IND), according to equation (6):

$$EFP = EFP_{DIR} + EFP_{IND} \tag{6}$$

where represents a product-specific EF associated with direct land use in forests, cropland, pastures, and built-up land necessary for the functioning of the production system, and is referred to as an "indirect" or "virtual land area" needed to absorb CO_2 emissions generated in the production process.

In this study, the EF of producing 1 m^3 of furniture board at enterprise "A" and the EF of producing 1 m^3 of solid structural timber at enterprise "B" were determined. These two wood processing companies are located in the western part of Ukraine and possess typical technological processes characteristic of enterprises engaged in the production of furniture boards and solid structural timber, respectively. The furniture boards are made from oak and beech wood, and the solid structural timber from fir and spruce wood.

According to the methodology, for each product, the EF associated with the direct use of forest land was determined, as well as the "virtual land area" required for absorbing the CO_2 emitted during the production process. The analysis of the production process of furniture boards and solid structural timber reveals that emissions of CO_2 and other greenhouse gases occur at the following stages:

– as a result of the burning of diesel fuel by internal combustion engines in automotive transport during the supply of raw materials to enterprises;
– as a result of the production of electrical energy for the operation of the technological equipment and lighting of production premises;
– as a result of the burning of wood waste to generate heat for lumber drying.

Results

1. EF associated with wood harvesting in the forests of Ukraine

When determining the area of direct land use, the lumber consumption rate to produce furniture boards (3.81 m^3/m^3) and solid structural timber (2.45 m^3/m^3) was considered, as well as the average timber stock per ha in Ukrainian forests (251 m^3) [State Forest Resources Agency of Ukraine 2022]. The direct land use required to produce 1 m^3 of boards at enterprise "A" is 0.015 ha, while for 1 m^3 of structural timber at enterprise "B" the value is 0.01 ha. Given the production volumes, the difference in land resource utilization is found to be significant.

2. EF associated with the raw material transportation process

The raw material in the form of round logs is delivered to the enterprises by means of road transport. As a result of burning diesel fuel by internal combustion engines, carbon dioxide, nitrogen oxide and methane are released, which are greenhouse gases. When calculating the "virtual land area" required for absorbing CO_2 as a result of raw material transportation, the following data were taken into account: the average transportation distance of raw materials, which depends on the location of the enterprise and its suppliers (for enterprise "A" – 200 km, for enterprise "B" – 30 km), the cargo capacity of the transportation vehicles (22 t), the average fuel consumption per 100 km (23 liters), and the density of freshly harvested timber (for oak wood – 990 kg/m^3, for fir wood – 760 kg/m^3). The calculations showed that the "virtual land area" required to absorb CO_2 to produce 1 m^3 of furniture board during the raw material transportation stage is 0.026 ha, and that required to produce 1 m^3 of solid structural timber is 0.002 ha. Transport plays a pivotal role in the EF, and strategic route optimization coupled with the adoption of eco-friendly transportation modes holds potential for mitigating its impact.

3. EF associated with producing electrical energy consumed by the operation of the technological equipment and lighting of production premises

When determining the "virtual land area" required to absorb the CO_2 generated during the production of electricity to power the technological equipment and lighting of production facilities for the manufacture of 1 m^3 of product, the following data were taken into account: average monthly production productivity (for

Table 1. Structure of Electricity Production in Ukraine, January 2022 [News of the Ukrainian Energy Exchange, 2022]

The method of electricity generation	Percentage in the structure, %
Nuclear power plants	55.0
Thermal power plant	29.3
Hydroelectric power station	6.7
Renewable energy (solar, wind, bio-stations)	8.0

Table 2. CO_2 emissions in the production of 1 kWh of electricity depending on the generation method [Atomic energy in Ukraine and the world, 2018]

The method of electricity generation	Greenhouse gasses emissions (g, CO_2 eq/kWh)
Renewable energy	20
Hydroelectric energy	33
Nuclear energy	35-60
Electricity generation by burning natural gas	400
Electricity generation by burning coal	1000

enterprise “A” – 200 m^3 of furniture board, for enterprise “B” – 500 m^3 of solid structural timber), average monthly electricity consumption (for enterprise “A” – 180,000 kWh, for enterprise “B” – 60,000 kWh), and the structure of electricity production in Ukraine. The structure of electricity production as of the beginning of 2022 is provided in Table 1 [News of the Ukrainian Energy Exchange, 2022]. CO_2 emissions during the production of 1 kWh of electricity, depending on the generation method, are provided in Table 2 [State Statistics Committee of Ukraine, 2011].

The stage of electricity generation emerges as pivotal in determining the comprehensive environmental impact. CO_2 emissions for the production of 1 m^3 of boards at enterprise “A” correspond to a value of 0.081 ha, while for 1 m^3 of structural timber at enterprise “B” the value is 0.011 ha. This accentuates the importance of optimizing the heat energy generation stage to reduce the EF.

4. EF associated with the process of generating heat energy

When determining the “virtual land area” required to absorb the CO_2 generated during the production of heat energy for drying lumber by burning wood waste, in the manufacture of 1 m^3 of product, the following data were taken into account: consumption of wood waste for wood drying to produce 1 m^3 of product (0.27 m^3 of wood waste for drying 1 m^3 of lumber or 688 kg of oak wood waste for the production of 1 m^3 of furniture board, or 171.3 kg of spruce wood waste for the production of 1 m^3 of solid structural timber), and the amount of greenhouse gases emitted in the process of burning wood (CO_2 – 1.304 kg/kg, N_2O – 0.023×10^{-3} kg/kg, CH_4 – 2.38×10^{-3} kg/kg) [State Statistics Committee of Ukraine, 2011].

The calculation results show that the “virtual land area” corresponding to the production of heat energy used in the drying of lumber by burning wood waste is 0.353 ha per cubic meter of furniture board and 0.088 ha per cubic meter of solid structural timber.

According to the calculations, the EFs of producing 1 m^3 of product from enterprise “A” and enterprise “B” were found to be 0.475 ha for furniture boards and 0.111 ha for solid structural timber, respectively. The structures of the EFs of furniture board production (enterprise “A”) and solid structural timber production (enterprise “B”) are shown in Figures 1 and 2.

5. EF associated with the process of generating heat energy using alternative sources

Based on the results of the EF calculation for the manufacture of 1 m^3 of product, it was found that

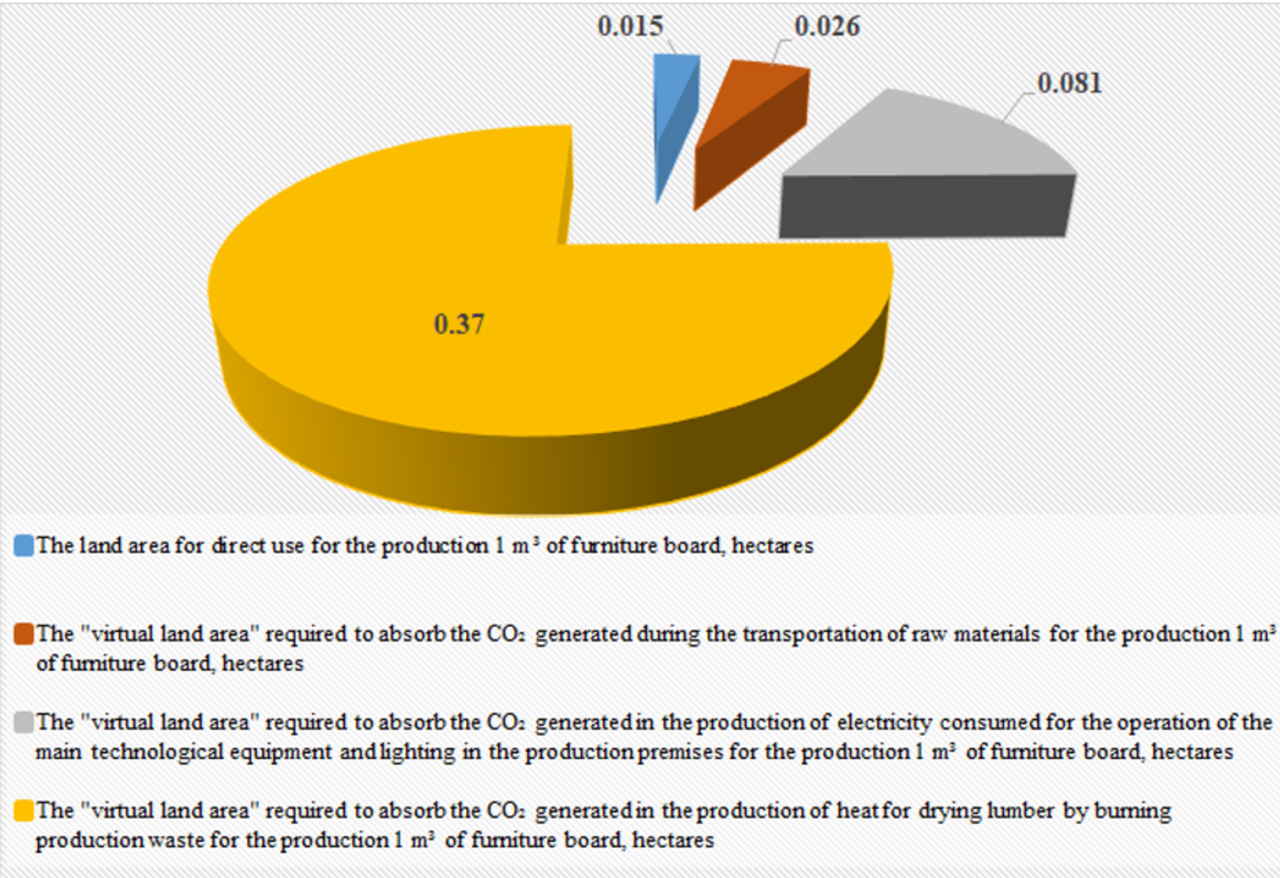

Fig. 1. Structure of the EF of 1 m^3 of furniture board manufactured at enterprise “A”

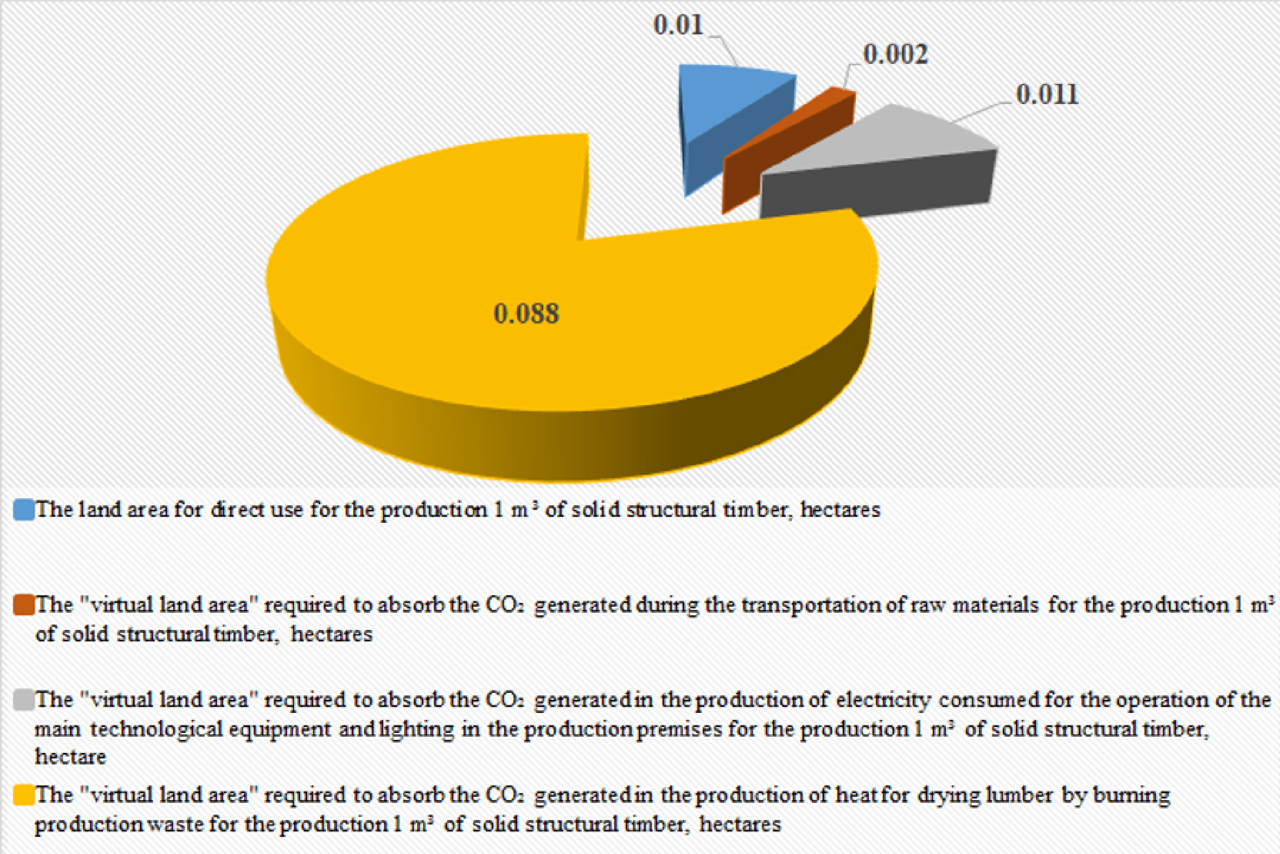

Fig. 2. Structure of the EF of 1 m^3 of solid structural timber manufactured at enterprise "B"

Table 3. The calorific capacity of some types of fuel [Volchyn et al. 2013]

Types of fuel	Calorific capacity, MJ/kg
Wood	19.77
Natural gas	35.6
Fuel oil	39.2
Coal	32.1
Electricity 1 kWh	3.6

most of the EF is associated with the process of generating heat energy for lumber drying. For enterprise "A" this accounts for more than 75% of the total, and for enterprise "B" more than 79%. With the aim of reducing the EF associated with the process of heat energy generating, an attempt was made to explore alternative sources of heat energy through theoretical calculations. Alternative sources of heat energy may include natural gas, fuel oil, coal and electrical power. The values of the calorific capacity of alternative heat energy sources are summarized in Table 3. Considering the calorific capacity of specific types of fuel, the amounts of them required for the lumber drying process in producing 1 m^3 of product were calculated. The calculation results are summarized in Table 4.

When calculating the EF of heat energy generation from the combustion of various types of fuel, the greenhouse gas emission indicators were considered (Table 5) [Main Department of Statistics of the Ternopil Region 2024].

The gross emission of greenhouse gas was calculated according to equation (7):

$$\mathrm{E_i} = k \times 10^{-6} \times Q_i^r \times B_i, \text{т} \qquad (7)$$

where:
k is an indicator of greenhouse gas emissions in the case of the i-th fuel, g/GJ;
Q_i^r is the lower heat of combustion of the i-th fuel, MJ/kg (Table 5);
B_i denotes consumption of the i-th fuel, t.

Table 4. The required amount of alternative sources of heat energy for drying the lumber for manufacturing of 1 m^3 of product

Types of fuel	Required amount of energy carrier, kg	
	Furniture board (enterprise "A")	Solid structural timber (enterprise "B")
Natural gas	382.1	95.1
Fuel oil	347.0	86.4
Coal	423.7	105.5
Electricity 1 kWh	3778.3	940.7

Table 5. Indicators of greenhouse gas emissions when burning different types of fuel

Types of fuel		Greenhouse gasses emission index k, g/GJ		
		CO_2	N_2O	CH_4
Natural gas	45.75	58,748.13	0.1	1.0
Fuel oil	38.78	76,662.63	0.6	3.0
Coal	20.47	93,740.0	1.4	1.0
Electricity (generated in the unified energy system of Ukraine)	-		235.3 g/kWh	
Electricity (wind energy and solar energy)	-		20 g/kWh	

Table 6. The results of the EF calculation for the process of generating heat energy to carry out the lumber drying process for the production of 1 m^3 of product using alternative sources of heat energy

Types of fuel	EF of the process of heat energy generation, ha	
	1 m^3 of furniture board (enterprise "A")	1 m^3 of solid structural timber (enterprise "B")
Natural gas	0.386	0.096
Fuel oil	0.388	0.097
Coal	0.306	0.076
Electricity (generated in the unified energy system of Ukraine)	0.333	0.083
Electricity (wind energy and solar energy)	0.028	0.007

The results of the EF calculation for the process of generating heat energy to carry out the lumber drying process to produce 1 m^3 of product using alternative sources of heat energy are summarized in Table 6.

A comparison of the EFs of the process of heat energy generation using different sources of heat energy for the drying of lumber to produce 1 m^3 of furniture board (enterprise "A") is shown in Figure 3. A similar comparison for the production of 1 m^3 of solid structural timber (enterprise "B") is shown in Figure 4.

A comprehensive exploration of alternative heat energy sources for wood drying is a key step toward addressing environmental concerns. Analysis of potential wood waste volumes under varied production scenarios facilitates the identification of effective waste management strategies, ensuring a harmonious balance between resource utilization and environmental conservation.

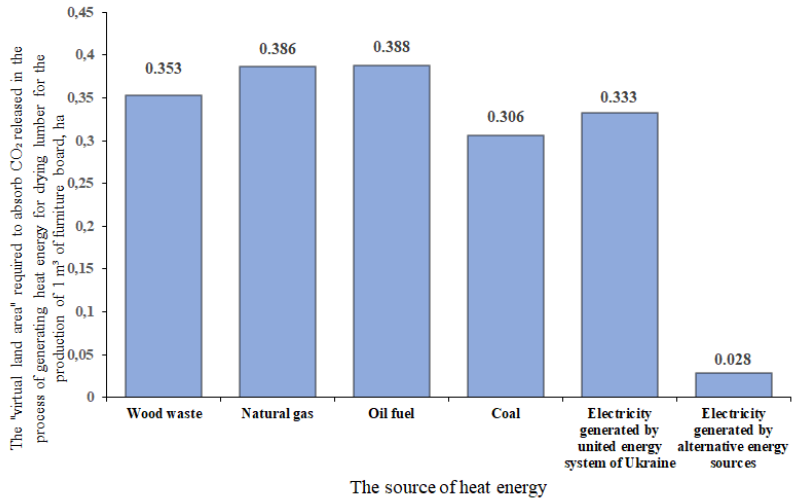

Fig. 3. EF of the process of heat energy generation using different sources of heat energy for lumber drying to produce 1 m³ of furniture board (enterprise "A")

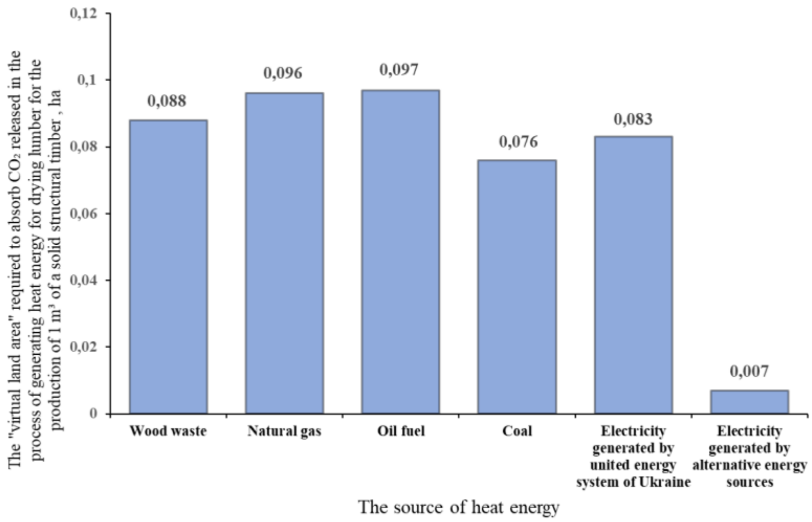

Fig. 4. EF of the process of heat energy generation using different sources of heat energy for lumber drying to produce 1 m³ of solid structural timber (enterprise "B")

6. Scaling the evaluation of the EF of furniture board and solid structural timber production within the entire industry

The results obtained were further scaled within the forest industry with various scenarios of usage of available raw resources. According to the State Agency of Forest Resources of Ukraine, based on the results of operations in 2022, 503,700 m³ of round timber of oak, 277,000 m³ of round timber of beech, and 142,400 m³ of round timber of ash were harvested in Ukraine [State Forest Resources Agency of Ukraine, 2022]. The total potential resources to produce furniture boards in Ukraine amounted to 923,100 m³. At the same time, 666,200 m³ of round timber of spruce and 149,900 m³ of round timber of fir were harvested, with a total potential amount of raw materials to produce solid structural timber equal to 816,100 m³.

Figures 5 and 6 show the EFs of potential production of furniture board and solid structural timber in Ukraine, depending on the volumes of raw materials used and the source of heat energy for the lumber drying process.

Also, an assessment was made of the potential quantity of released wood waste, currently used as fuel to generate heat energy for the lumber drying process, assuming that it is replaced by an alternative energy source, particularly electricity. The results of calculations for potentially released quantities of wood waste, depending on the production scenario, are shown in Figures 7 and 8.

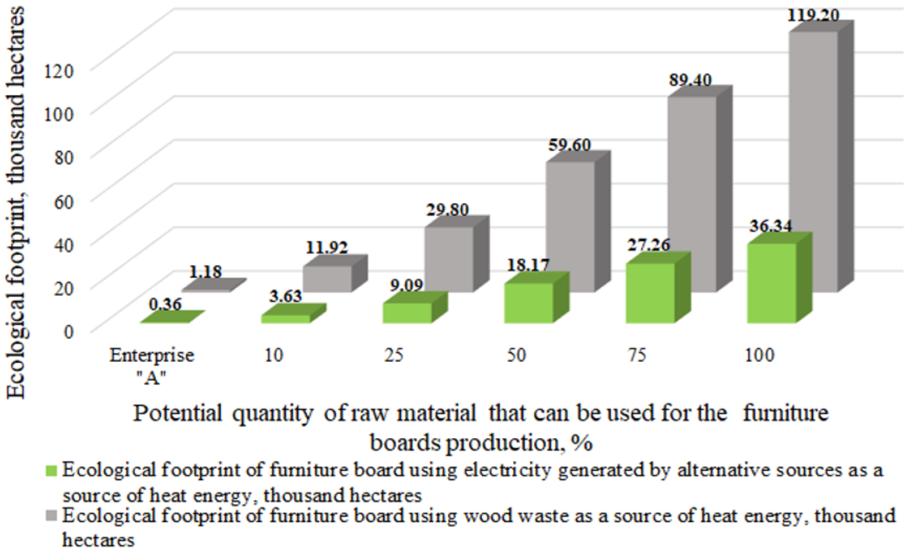

Fig. 5. EF of potential production of furniture board in Ukraine

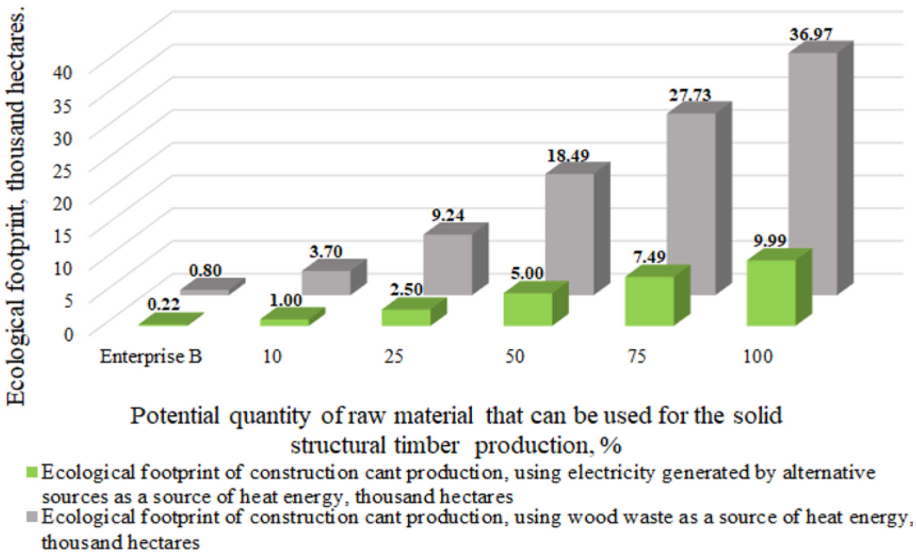

Fig. 6. EF of potential production of solid structural timber in Ukraine

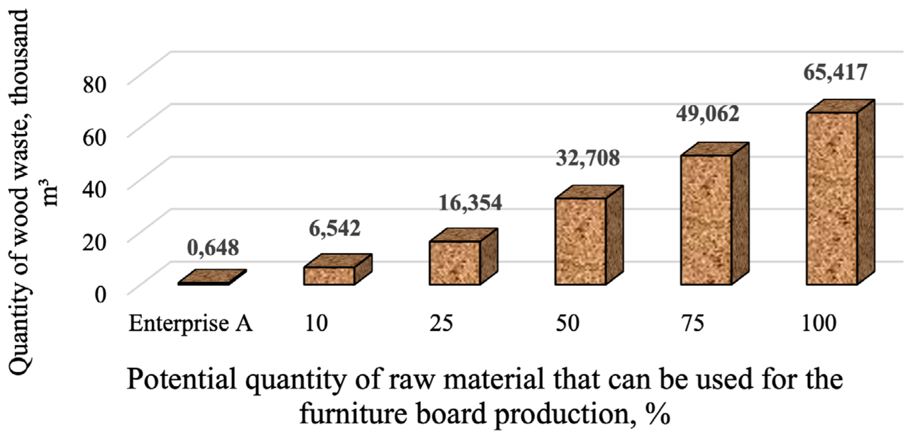

Fig. 7. Potential quantity of released wood waste depending on scenario for the production of furniture board in Ukraine

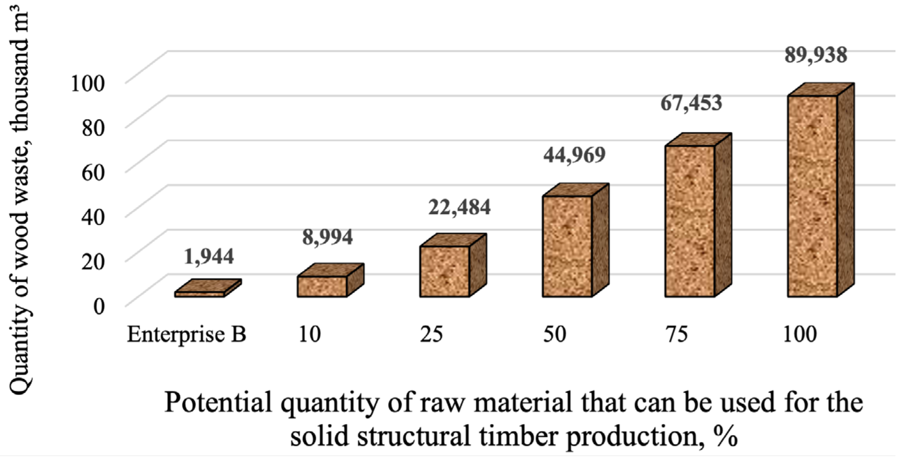

Fig. 8. Potential quantity of released wood waste depending on scenario for the production of solid structural timber in Ukraine

Discussion

The conduct of a comprehensive environmental impact assessment for the entire forest sector in Ukraine, while factoring in raw material consumption volumes, lays the groundwork for anticipating the forest industry's EF trajectory. Such an analysis forms the bedrock for devising strategies geared towards balanced and sustainable development. The results of Szarka et al. [2023] provide further insights into this endeavor. Their development of a guideline for establishing flexible dynamic bioeconomy platforms – Regional Bioeconomy Hubs (RBHs) – provides a structured approach for engaging stakeholders from policy, academia, industry, and society. By applying this guideline to five Central and Eastern European regions, including Ukraine, the *"emPOWERing regional stakeholders for realising the full potential of European BIOeconomy"* (POWER4BIO) project – which aims to empower regional stakeholders to realize the full potential of the European bioeconomy – has facilitated the successful establishment of Regional Bioeconomy Hubs (RBHs) and the formulation of regional bioeconomy strategies. This project enhances the capacity of regional and local policymakers and stakeholders to structure their bioeconomy and supports the emergence of a thriving bio-based sector through adequate knowledge exchange and networking within and among regions across the EU. Developed strategies, validated through the project, serve as actionable frameworks for sustainable development in the respective regions, providing a model for Ukraine's forest sector and beyond.

Sustainable industry development scenarios require not only optimizing production within individual enterprises but also embracing innovative technologies and energy-efficient solutions at the sectoral level. This includes considering alternative heat energy sources and streamlining transportation strategies, both of which synergistically contribute to an overarching reduction in the industry's environmental impact.

In the specific context of this study, it is important to note that the EF assessments were conducted on enterprises implementing typical production and technological processes characteristic of Ukrainian wood-processing enterprises. Consequently, it can be inferred that the EF per unit of production for similar products across other enterprises in the sector would likely be comparable. However, a notable limitation is that the EF analysis focused only on the basic production stages of wood-based products, without incorporating the impact of production waste. Each studied enterprise treats waste as a resource for manufacturing additional products, which aligns with circular economy principles, but may affect overall environmental calculations.

In conclusion, scaling the evaluation of EF within the furniture board and solid structural timber production industry demands a multifaceted approach. By amalgamating data-driven assessments, strategic foresight, and collaborative endeavors, decision makers can chart a course towards a more sustainable and environmentally conscious future for the Ukrainian forest sector.

A recent study deploys data from the EU-23 from 2010 to 2020 using panel regression methods and explores the long-term relationships between ecological footprint types and circular economy indicators, such as per capita municipal waste generation, the municipal waste recycling rate, investment, the circularity rate, and trade in recyclable materials [Chen and Pao 2024]. That study found that ecological footprints showed negative or minimal growth, except for forest footprints, which reflects the unique pressures faced by regions heavily reliant on natural resources, such as the Ukrainian Carpathians. It led the authors to the conclusion that the EU should also diversify investments beyond energy efficiency, including protecting old-growth forests and forest biodiversity, restoring forest landscapes and ecosystems' resilience, and enhancing forests' role in climate change mitigation and adaptation. This perspective is particularly relevant for the Ukrainian Carpathians, a region where socio-economic challenges, such as high unemployment and low-income levels, contribute to unsustainable forest practices and a rising EF of wood-based products. The ongoing conflict has further strained these ecosystems, making it imperative to assess and mitigate environmental impacts through informed policy decisions. Considering these findings, the discussion of EFs in production processes becomes crucial for formulating effective strategies aimed at environmental impact mitigation and within the forest sector. This includes integrating insights from both the EU context and the specific challenges faced by Ukraine as a candidate country for EU membership, emphasizing the need for sustainable forest management practices that align with circular economy principles. Such strategies will not only foster long-term ecological balance and resilience in the Carpathians, but also contribute to broader EU goals of sustainability and environmental stewardship.

Conclusions

Deep analysis of alternative sources of thermal energy for wood drying emerges as a pivotal measure in addressing environmental challenges within the wood-processing industry. Notably, the utilization of natural gas presents itself as a cleaner alternative to traditional fuels, offering substantial reductions in greenhouse gas emissions during production processes. Moreover, the concurrent integration of solar and wind energy holds promise in diminishing reliance on conventional energy sources, thereby fostering sustainability in operations.

The findings derived from an example examination of the EF associated with furniture boards and solid structural timber production at the enterprises "A" and "B" underscore the urgent need for measures aimed at mitigating this impact. The optimization of processes alongside the adoption of environmentally friendly technologies emerges as instrumental in achieving a notable reduction in the industry's EF.

Furthermore, the necessity of conducting a comprehensive environmental impact assessment spanning the entire sector cannot be overstated, as it serves as a foundational step in projecting the industry's future EF trajectory. In tandem with this assessment, industry-wide scenarios should encompass endeavours directed at enhancing production efficiency at individual enterprises and deploying energy-efficient solutions across the sector. Central to this approach is the thorough scrutiny of alternative sources of thermal energy and the implementation of optimized transportation strategies, both of which are integral to affecting a systemic reduction in the industry's environmental impact.

Effective management of wood waste necessitates meticulous attention to both the quantities of released waste and the formulation of pragmatic waste management strategies. Particularly salient is the discourse surrounding the ramifications of utilizing wood waste for thermal energy production, an aspect that holds profound implications for sustainable development initiatives. Transitioning towards alternative energy sources, such as solar and wind energy, not only facilitates enhanced material utilization of wood waste, but also contributes significantly to the ecological sustainability of production processes.

Moreover, the strategic application of technologies geared towards harnessing wood waste in sustainable processes assumes paramount importance in fostering environmental stewardship within the industry. Recommendations for wood waste management must be crafted with due consideration for potential political ramifications, thereby ensuring alignment with broader policy objectives aimed at sustainability.

In conclusion, a nuanced examination of alternative sources of thermal energy and wood waste management strategies underscores their pivotal role in steering the industry towards sustainable development pathways. By leveraging improved production processes and the integration of environmentally friendly technologies, recommendations serve as linchpins in striking a delicate balance between production imperatives, economic interests, and environmental stewardship within the timber production industry.

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