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Impact of Drought on the Life Cycle of Barge Transport

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Abstract

This paper aims to analyze the impact of drought on the life cycle of barge transportation. The LCA method was used to quantify the environmental impact of barge transportation services on the Madeira River/Brazil: Transportation Operation, Barge Fleet, and Waterway Infrastructure. A model for barge convoy formation was developed as a function of river water level variation. From this, the transport operation was simulated, considering the loading of grains from the Madeira River in 2021, as well as the respective fuel consumption and CO_{2Eq} emissions. The results indicate that barge transportation is more harmful to the environment during drought, since only a convoy of nine barges is allowed to navigate, and its energy efficiency is compromised due to the longer travel time and lower loading capacity in one trip. The intense use of this barge convoy implied an increase of 22.25% in CO_{2Eq} emissions when compared to the full river.

Keywords: Barge; Drought Impacts; Life Cycle Assessment (LCA); External Costs; Madeira River.

1. Introduction

The transport sector is the main driving force for economic and social development, besides allowing the integration of a country with large land dimensions, such as Brazil. The worsening of the projections of future climate change scenarios increases the pressure to reduce emissions of pollutants, where the transportation sector is central because of the intense use of fossil fuels, making it one of the main contributors to global warming [1, 2]. Soybeans and corn are the most important agricultural commodities traded in the world, with Brazil as one of the leading exporters of soybeans and corn in 2021 [3]. The Midwest region of Brazil is the principal producer hub of these commodities, whose most sustainable logistics infrastructure lies in the country's northern reaches [4].

However, 65.63% (69.945 million tons) of the total grain is exported through south and southeast harbors [5], whose road infrastructure is predominant. Only 31.32% (33.76 million tons) of the grains use the ports in the northern area. On the other hand, the transport infrastructure available to the ports in the north harbors area uses a combination of road transport and the Madeira River [6]. The advantages of Inland Waterway Transport (IWT) make this mode of transport more suitable for the transportation of low-value-added cargo, such as agricultural commodities: greater energy efficiency, lower emission of pollutants, and greater cargo capacity, among others [7, 8]. However, long travel times, high investments in infrastructure/adequacy of infrastructure, and susceptibility to hydrological regimes are some disadvantages of IWT [9]. Susceptibility to hydrological regime occurs when there is a significant reduction in the water level. The impact of IWT is; (i) reduction in carrying capacity; and (ii) restriction in navigation, such as lower speed and time window for navigation [10].

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The Madeira River has very well-defined periods of flood and drought, whose water level amplitude can reach 13 meters, and it is common for navigation to be prohibited [11]. In this context, barge convoys become less efficient in relation to the higher water level due to the reduction in loading capacity and a higher fuel consumption per ton-km, which leads to an increase in pollutant emissions [10]. The LCA method is widely used to measure the environmental impact on transportation systems. The processes and rules for its elaboration are set by the International Organization for Standardization (ISO) through technical standards [12]. Spielmann & Scholz [13] quantified the exhaust emission of the transport services of the freight transport modes (road, rail, water, air) in Switzerland. The transport service structure was composed of seven components: vehicle operation (P_1), manufacturing (P_2), maintenance (P_3), final fleet allocation (P_4), construction (P_5), operation (P_6), and final allocation of waterway infrastructure (P_7). The case study was a 250 km waterway segment in Switzerland, with an average capacity of 1,000 tons of cargo per barge. The results indicated that barge operations are the primary source of GHG emissions.

Building on this work, Van Lier & Macharis [14] evaluated the environmental impacts of inland waterway transport services. In the model, the authors consider nine barge types and seven waterway types (located in Belgium). The barge used as a reference has a capacity ranging from 801 – 1,000 tons, and the route measures 27 km (Brussels-Scheldt Canal). Like the results of Spielmann & Scholz [13], the barge trips (operations) concentrated almost 70% of the total CO_2 emissions. Bates et al. [15] determine the environmental impacts of processes up to the final placement of sediment material dredged from rivers using the LCA method. The case study occurred in the Long Island Sound (LIS), a region of the United States, whose characteristics were (1) open water, (2) uplands, and (3) containment island. The authors used an approach to measure and aggregate the effects of Midpoint on Endpoint scores. The results showed that most emissions come from fossil fuel consumption in barge travel. Duan et al. [16] formulated a simplified LCA to quantify CO_2 emissions from the transportation system in China. This method maps the intrinsic attributes of transportation operations concerning energy use and carbon emissions. The results highlighted that barge transportation is the least environmentally damaging and the one that moves the most cargo in China.

Merchan et al. [17] determined the externality of domestic freight in Belgium (road, rail, and river) and converted it into external costs. The authors considered Midpoint and Endpoint environmental impact categories. The results showed that the rail mode of transport had a lower environmental impact than the inland waterway mode of transportation, which may be the result of engines with more modern technology. Perčić et al. [18] evaluated the environmental and economic impacts of using seven different energy sources (electricity, methane, liquefied natural gas (LNG), hydrogen, ammonia, and biodiesel) on three types of waterway vessels in Croatia; cargo, passenger, and dredging. The results indicate that electricity is the least harmful to the environment, with ammonia at the opposite extreme. Diesel was the third most damaging, with GHG emissions occurring primarily in burning this fuel (PWT). Fan et al. [19] evaluated the environmental impact of different propulsion systems on four main types of waterway vessels used in China. The propulsion systems are diesel-powered and hybrid-powered, which is a combination of battery electric and LNG. The authors identified the most suitable power source for the vessel types. The results indicated that the hybrid propulsion system emits 33.44% less GHG than the diesel propulsion system. The life cycle stage that showed the most emission reduction was in fuel consumption (PTW), a 40.49% reduction compared to the diesel propulsion system.

Perčić et al. [20] developed a model to evaluate the environmental and economic impact of different propulsion system configurations for three types of waterway vessels used in Croatia; cargo, passenger, and dredging. The propulsion systems under consideration are diesel-powered, photovoltaic cells, electric batteries, and a combination of photovoltaic cells and electric batteries. The results indicated that the diesel propulsion system was the most environmentally damaging of all three vessel types. Wang et al. [21] evaluated and compared the environmental impact of different propulsion systems used in ferries (battery and diesel power). The results indicated that the battery-powered propulsion system emits 29.51% less $CO_{2\ Eq.}$

According to this literature search, no work has found that considers the impact of a variable exogenous to the transportation system, such as water level, on the life cycle of THI. Furthermore, the case study of this research is about a waterway in the Amazon region of Brazil. In view of this, this work aims to analyze the impact of drought on the life cycle of barge transportation. For this purpose, an operation model of bulk barge transport depending on the water level of the Madeira River was developed.

The present study consists of five sections, including this introduction. Section two shows the literature review of the LCA method and IWT's applications. Section three presents the methodological procedure. Section four describes the results and discussion, and the fifth section shows the conclusion.

2. Literature Review

2.1. LCA

The International Standardization Organization (ISO) recognizes the application of the Life Cycle Assessment (LCA) as an international analytic tool for environmental management and sustainability [12]. LCA methods aims to quantify the environmental impact and human health burden associated with multiple stages of a product or service's life cycle. It starts with raw material extraction, production of energy and materials, manufacturing, use, and finally disposal, including recycling if feasible [12, 22, 23]. The LCA study comprises four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The goal definition sets the context and determines the purpose of the LCA study. Then, the scope of the LCA study considers the functional unit, which activities and processes belong to the product/service life cycle in context (extent of the transport system), selecting the assessment parameters (i.e., impacts to evaluated), establishing the geographic and temporal limits and choosing the relevant perspective to apply in the study [24]. The second phase, inventory analysis compiles information around the physical flow in terms of input of resources materials, semi-products and products and the output of emissions, waste and valuable products for the product system. The results of the inventory analysis is the life cycle inventory (LCI), a list of quantified physical elementary flows for the product system that is associated with the function described by the functional unit life cycle impact assessment (LCIA).

The Life Cycle Impact Assessment (LCIA), third phase of LCA, aims to evaluate the weight of each elementary flow (emissions or resources use of a product system) in terms of environmental impact. For this, the ISO (2006) states that it is necessary to achieve at least the first three elements of the five defined in the standard, namely:

- Define of impact category in conformity with the objective and scope of the study (phase 1);
- Classify elementary flows by relating them to the impact categories;
- Select impact categories, characterized through environmental models, attributing measurable values or quantities;
- Normalize impact categories scores to identify their relative magnitude (expressed in the same unit of measurement); and
- Grouping or assigning weight for comparison between impact categories and possibly ranking them according to their perceived severity.

The product system was evaluated from an environmental perspective using the impact categories indicators and with the inventory analysis results. Therefore, this provides valuable information for the interpretation phase. Finally, the interpretation (phase 4) aims to answer questions posed in phase 1. The interpretation is based on objective and scope, given the constraints defined, such as the geographic, temporal, or technological assumptions.

2.2. LCA in IWT

Four works aimed at assessing the environmental impact of different types of propulsion systems and fuels for ships [19–21]. Merchan et al. [17], van Lier & Macharis [14], and Spielmann & Scholz [13] applied the LCA method to assess the Environmental impact of waterway transport services related to infrastructure, barge fleet, and transport operation. Bates et al. [15], and Duan et al. [16] evaluate the environmental effect of freight using the LCA method (Table 1).

Table 1. Surveyed papers that applied LCA to the IWT

Source	Research aim	Midpoint Environmental Impact Category	River	Country
Wang *et al.* (2021) [21]	Compare the environmental impact of two propulsion systems for ferries (diesel and battery electric).	Climate Change	Thames River	UK
Fan *et al.* (2021) [19]	Evaluate alternative solutions for the propulsion system of waterway vessels that are less harmful to the environment and economically viable.	Climate Change	Yangtze River	China
Perčić *et al.* (2021) [18]	Establish a model to investigate the application of different configurations of propulsion systems in the environmental and economic context, aiming to retrofit three different types of vessels.	Climate Change; Acidification; Photochemical Ozone Formation; Particulate Matters.	Danube River, Sara River, Drava River and Kupa River	Croatia
Perčić *et al.* (2021) [20]	To technically and economically evaluate fuel alternatives for three types of waterway vessels (passenger, cargo, and dredging) to reduce CO2 emissions.	Climate Change	Sava River	Croatia
van Lier & Macharis (2014) [14]	Assessing the environmental impact and external costs of IWT transport services	Climate Change; Material Particulado; Acidification; Ecotoxicity; Photochemical Ozone Formation.	Upper Scheldt; Canal Ghent–Bruges; Canal Leuven–Dijle; Canal Roeselare–Leie; Canal Brussels–Scheldt; Albert Canal; Main-Donau Canal.	Belgium
Merchan *et al.* (2019) [17]	Calculate the externalities and external costs of the services of road, rail, and inland waterway modes of transport.	Climate Change; Stratospheric Ozone Depletion; Acidification; Eutrophication; Photochemical Ozone Formation; Human Toxicity; Particulate Matter Formation; Ionising Radiation; Land Use; Water Use.	Not Informed	Belgium

Spielmann & Schols (2005) [13]	Quantify emissions associated with transportation services by IWT.	Climate Change; Stratospheric Ozone Depletion; cidification; Eutrophication; Photochemical Ozone Formation; Human Toxicity; Particulate Matter Formation; Ionising Radiation; Land Use; Water Use.	Not Informed	Switzerland and Europe
Bates *et al.* (2015) [15]	Assess the environmental impact associated with the deposition of dredged material.	Climate Change; Stratospheric Ozone Depletion; Acidification; Eutrophication; Photochemical Ozone Formation; Human Toxicity; Particulate Matter Formation; Ionising Radiation; Land Use; Water Use.	Long Island Sound (Estuary)	USA
Duan *et al.* (2015) [16]	Estimate the carbon emissions of transport modes in terms of freight and passenger volume	Climate Change	Not Informed	China

Climate Change was the most widely used intermediate environmental impact category in all papers. European countries concentrated most of the case studies, with six papers, two papers occurring in China and one paper in the USA. In this literature survey, no studies considered the impact of an exogenous variable on the life cycle of the inland waterway mode of transport. Furthermore, no studies case considered South America, where Brazil has one of the largest hydrographic networks in the world (see international references). In this context, such research gaps justify this work.

Table 2 presents the input and output data of the transport service components extracted from the literature review. Barge trips were the main research object, and just three papers quantified all transport services emissions, such as those by Spielmann & Scholz [13], van Lier & Macharis [14], and Merchan et al. [17].

Table 2. Input and output data of transport service components from literature review

Authors	Barge Operation Data		Inputs		Outputs ($g\ CO_2/tkm$)							Country
	Barge Capacity	Length. (Km)	$\frac{g\ CO_2}{Kg_{Fuel}}$	$\frac{g_{Fuel}}{tkm}$	Barge Operation		Barge Fleet		IWT Infrastructure (Channel & Port Facilities)		Total Emission	
					Barge Trip	Precombustion	Manufacture	Maintenance	Build	Operation & maintenance		
Spielmann & Schols (2005) [13]	1000	250	3172	9.00	74.7	7.97	1.99	0.498	13.9	0.498	99,6	Switzerland
van Lier & Macharis (2014) [14]	1050	27	3100	9.39	36.9	10.8	0.967	0.139	6.07	0.197	55,1	Belgium (Flanders)
Bates *et al.* (2015) [15]	1962	16,0934	3172	9.00	74.7	N/A	N/A	N/A	N/A	N/A	74,7	USA
Duan *et al.* (2015) [16]	1000	N/A	N/A	N/A	55.0	N/A	N/A	N/A	N/A	N/A	55,0	China
Merchan *et al.* (2019) [17]	1000	1417	3172	6.73	21.7	3.74	1.49		47.8		74.7	Belgium
Perčić *et al.* (2021) [18]	967	223	3206	11.38	88.0	N/A	N/A	N/A	N/A	N/A	88,0	China
Fan *et al.* (2021) [19]	1880	6000	3206	2.73	8.70	N/A	N/A	N/A	N/A	N/A	87,0	China

3. Research Methodology

3.1. LCA Method

The LCA method measures the environmental impact in a complex system, such as freight transport, quantifying the use of resources and the emissions generated in transport services (barge operation, barge fleet, and IWT infrastructure) [12]. The method identifies opportunities for improvements in the environmental performance of the product system [17]. The LCA consists of four phases (Figure 1): Phase I: definition of objective and scope; Phase II: Life Cycle Inventory (LCI); Phase III: Impact Assessment (LCIA); and Phase IV: Interpretation.

The first phase is the definition of the goal and the scope, which in this research is to quantify the GHG emissions from the IWT in rainy and drought seasons. The functional unit is the unit of measurement with reference to the material and energy flows that constitute the life cycle processes. This paper used one ton-kilometer (ton-km) of grain transported in barge convoys through one kilometer of an inland waterway. The second phase developed the LCI, collecting and compiling data in the production function, according to phase I. This paper used data from technical reports from the government of Brazil, the Ecoinvent v3.7.1 database, and sources in the scientific literature. The third step is the ICV impact assessment, which aims to study the significance of potential environmental impacts. The ICV data was translated into environmental impacts through science-based models. It is necessary to select the most appropriate impact category, which encompasses the most relevant environmental issues for the object of study. An impact category includes impact category indicators (quantifiable representation of an impact category) and characterization models, which convert an assigned LCI result into the unit of measuring the impact category indicator through the characterization factors [25-27].

Indicators can be intermediate (midpoint) or final (endpoint), which depend on the degree of detail in the cause-effect chain. Figure 2 presents the relationship between the environmental mechanisms, i.e., the 17 midpoint and three endpoint impact categories [28].

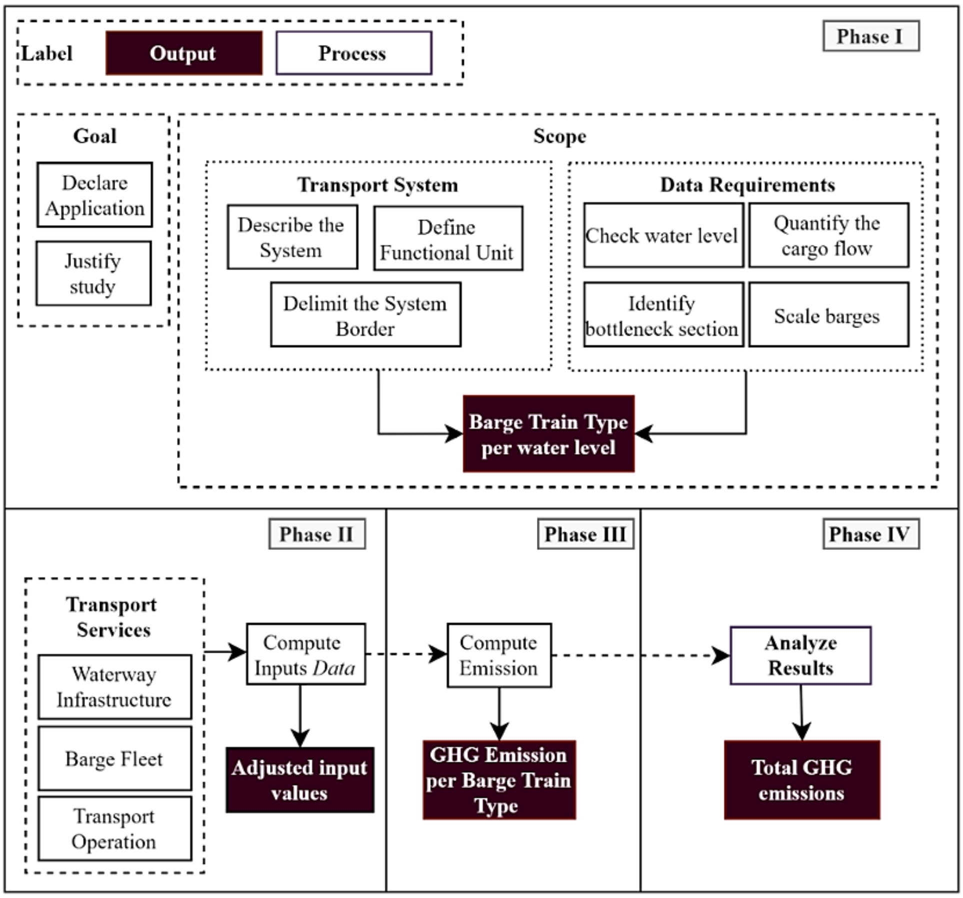

Figure 1. Processes adopted in the phases of the barge transport life cycle

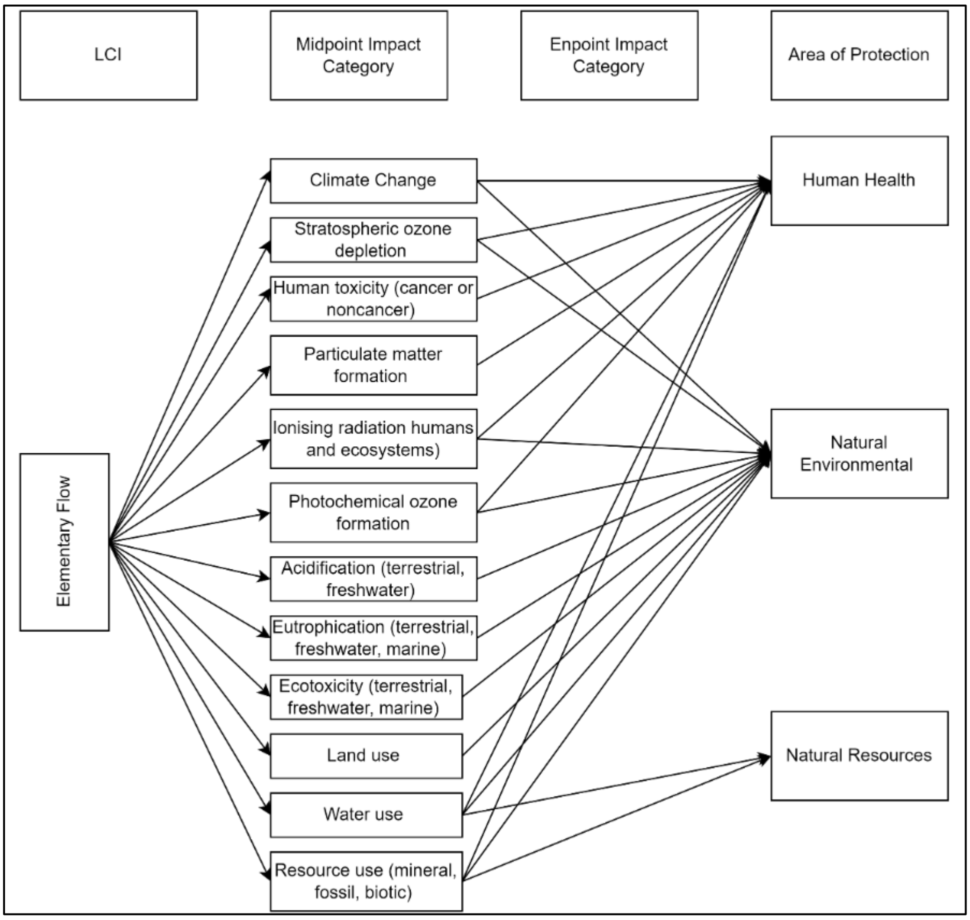

Figure 2. LCIA framework relating elementary flows to intermediate and final impact category indicator results (Adapted [27])

This paper adopted the CML-IA baseline, developed by Guinée et al. [29], to quantify the GHG emission. The characterization model used by this method was developed by the Intergovernmental Panel on Climate Change (IPCC), taking the global warming potential over a 100-year horizon (GWP_{100a}) as a factor [30, 31]. A case study is presented below starting with the characteristics of the Madeira River, hydrological conditions, and model and barge transport operation.

3.2. Grain Barge Transport

The transport of barges takes place on the stretch of the Madeira River located between the port of Porto Velho/RO (origin) and the port of Itacoatiara/AM (destination), as shown in Figure 4. This stretch has a length of 1080 km, an average width of 1.4 km, and a slope of 1.7 cm/km [32].

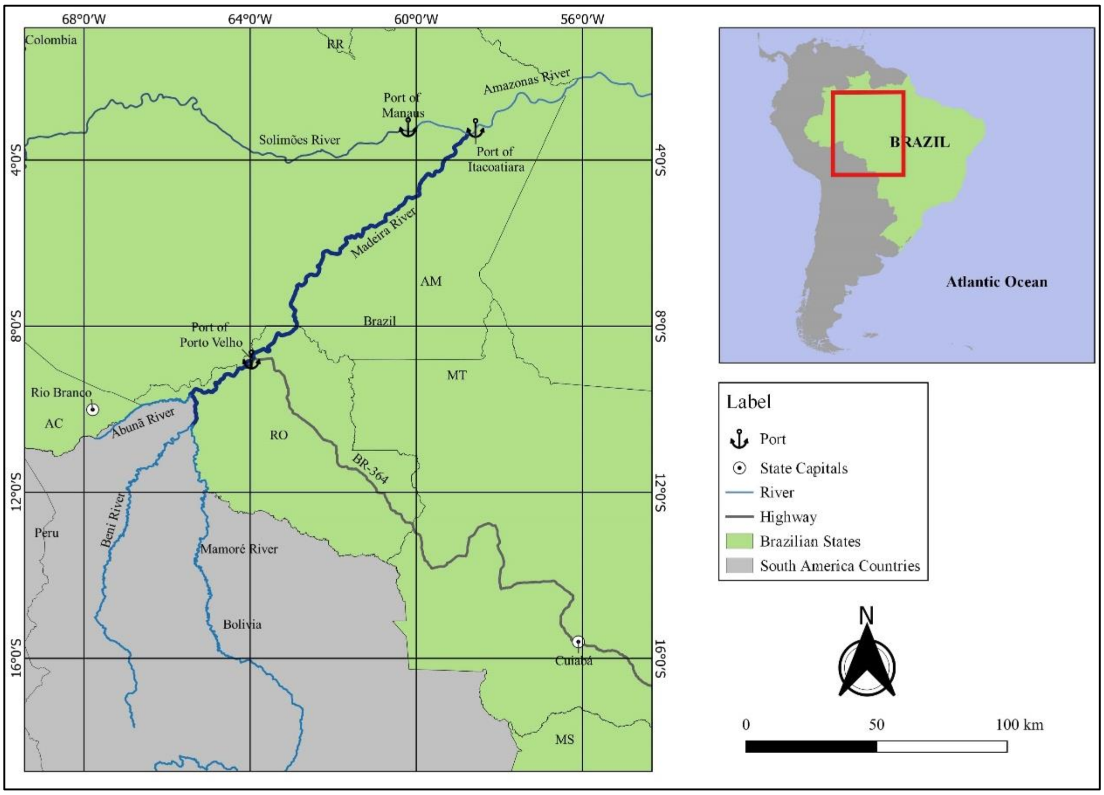

Figure 3. Export route for agricultural commodities in the Midwest of the country

The hydrological conditions of the Madeira River change dramatically throughout the year. The hydrological data of the Madeira River, extracted from the National Water Agency database, known as Hidroweb v.3.2.6 [33], reveals that the flood season occurs between February and June. The average water level in the rainy season was 13.685 meters. On the other hand, the drought season occurs between August and November, when the water level reaches 3.158 meters Figure 3.

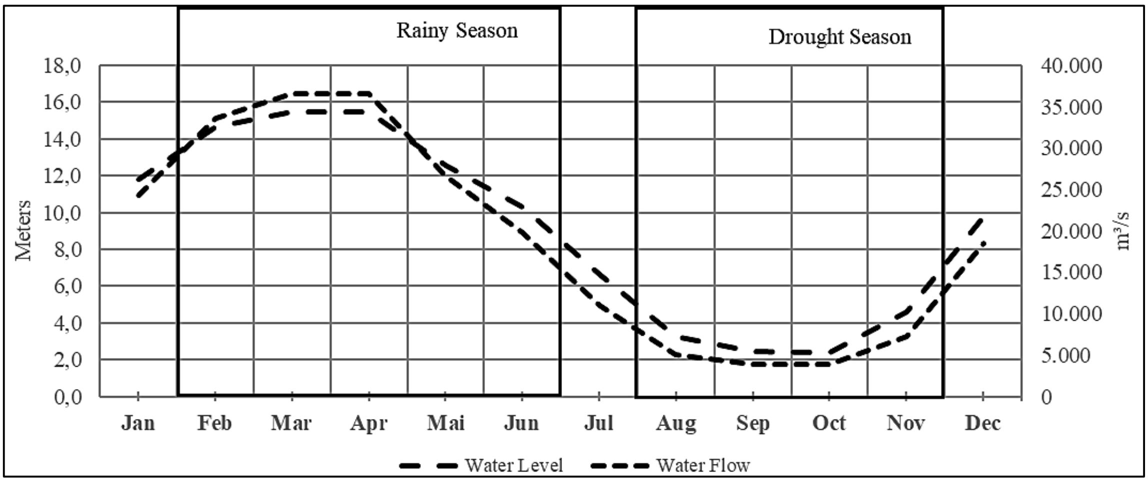

Figure 4. Madeira River water level and water flow in 2021

Porto of Porto Velho/RO fluviometric station adopts because of its use by the Brazilian Navy in navigation decisions. For the level below four meters, the Brazilian Navy prohibits night navigation and restricts draft to 2.3 meters [11]. Sale in these conditions is dangerous in the Marmelos Passage, a stretch of 15.56 km, between nautical miles 299 and 302 of the river mouth, which sandbanks formation and rocky geomorphology at the bottom and on both sides of the river. Given this, the formation of barge convoys is a function of the water level. Table 3 presents the physical dimensions of the barge convoys and the maximum draft allowed due to navigation restrictions (34-37).

Table 3. Features of bulk barge convoys on the Madeira River

Description	Quantity of Barges			
	9	**12**	**16**	**20**
Formation of Barge convoy	3×3	3×4	4×4	4×5
Length (meters)	210	240	240	270
Width (meters)	33	33	44	55
Maximum Allowed Loading (ton)	8550	24000	32000	40000
Water Level (meters)	≤ 4	≤ 10	≤ 12	> 12
Maximum Allowable Draft (meters)	1.8		3.6	

3.2.1. Diesel Consumption

The Diesel Consumption in Trips j of the convoy of barges i (CDV_{ij}) is presented in Equation 1, where P_{D_i} is the Available Power of the convoy of barges i (HP); C_e Specific Diesel Consumption ($Liters_{Diesel}/hour.HP$); and (T_T) the Total Travel Time (hours). In this research, the specific diesel consumption value adopted was 0.2 liters per HP-hour extracted from the work by Brazil and INECO [37], as it deals with the transport of grains in the Madeira River waterway.

Equation 2 presents the Available Power of the Barge Convoy (P_{D_j}), where P_{I_i} is the Installed Power of the Barge Train j (HP); and P_U the Power Used of the motor (%). The Total Travel Time (T_T) is given by the sum of the Outbound (T_1) and Return (T_2) Travel Times, according to Equation 3.

$$CDV_{ij} = \left(P_{D_i} \times C_e\right) \times T_T \tag{1}$$

$$P_{D_i} = P_{I_i} \times P_U \tag{2}$$

$$T_T = T_1 + T_2 \tag{3}$$

The Travel Times (round trip) in rainy and drought seasons extract from the paper of Creech et al. [35], according to Table 4. In high water, part of the driving force of barge convoys is generated by the current strength on the outbound trips, while on the return trips, the flow strength acts as a resistance force, making navigation difficult. On the other hand, in the drought season, the flow strength is significantly lower, with the round trip and return times close.

Table 4. Travel times for bulk barge convoys on the Madeira River

Description	Quantity of Barge			
	9	**12**	**16**	**20**
One-Way Travel Time (Hours)	92	60	60	60
Return Travel Time (Hour)	100	130	130	130
Total Travel Time (Hours)	192	190	190	190
Specific Fuel Consumption (g_{Diesel}/tkm)	4.375	3.702	3.085	3.085

The Diesel Consumption per ton-km – measured in $litros/tkm$ – presents to Equation 4, where A_i is the number of Berthing needed by the convoy of barges i to transport the grains moved in the Madeira River in 2021; MT_i the Transport Moment of the barge convoy i; and d is the distance of the segment Equation 6. In 2021, about 3.726 million tons of grain transported through the Madeira River. Equation 5 presents the calculation that determines A_i, where TC is the Total Cargo transported through the Madeira River in 2021; and CC_i is the Cargo Capacity of the barge convoy under analysis (i).

$$CDT_i = \frac{A_i \times CDV_i}{MT_i} \tag{4}$$

$$A_i = \frac{TC}{CC_i} \tag{5}$$

$$MT_i = MC_i \times d \tag{6}$$

Finally, the calculation for MT_i is presented in Equation 6, where MC_i is the Cargo Movement of barge convoy i and d is the distance of the section. The conversion value of 841.043 Kg_{Diesel}/m^3 adopted to convert the unit of measuring liters to kg [38]. The results of Equations 1, 4, 5, and 6 are presented in Table 5.

Table 5. Operational features of barge convoys on the Madeira River

Description	Barge Convoy			
	9	**12**	**16**	**20**
Berthing – A_i	436	156	117	94
Transport Moment (billions of ton-km) – $MC_i \times d$	4.026	4.044	4.044	4.061
Diesel Consumption in the Travel (millions of Kg) – CDV_i	16.897	14.358	11.965	12.016
Diesel consumption per ton-km (g_{Diesel}/tkm) - CDT_i	4.197	3.551	2.959	2.959

3.2.2. Barge Transport Life Cycle

Spielmann & Scholz [13] developed a generic model of the structure of transport services by mapping the road transport life cycle. This life cycle model allowed van Lier & Macharis [14] to determine the life cycle of inland waterway transport. From these two works, the barge transport life cycle was developed (Figure 5) [14, 39], whose services are related to the Transport Operation, the Barge Fleet, and the Waterway Infrastructure, as detailed below:

- ***Transport Operation:*** Consists of an emission in Barge Operations (P1) due to burning diesel processes in the tugboat engines during trips. This component considers oil extraction, transport, storage, diesel refining (pre-combustion), and consumption.
- ***Barge Fleet:*** Consists of emissions related to Manufacturing components (P2), Maintenance (P3), and Final Disposal (P4). This transport service considers the resources used in manufacturing for one barge with one thousand tons capacity, with a lifespan of 1.24 million km.
- ***IWT Infrastructure:*** This service consists of emissions related to the Construction (P5), Maintenance and Operation (P6), and Final Disposal (P7) components of the IWT Infrastructure, with a useful life of 118 years. The reference unit of measurement is the year x meter.

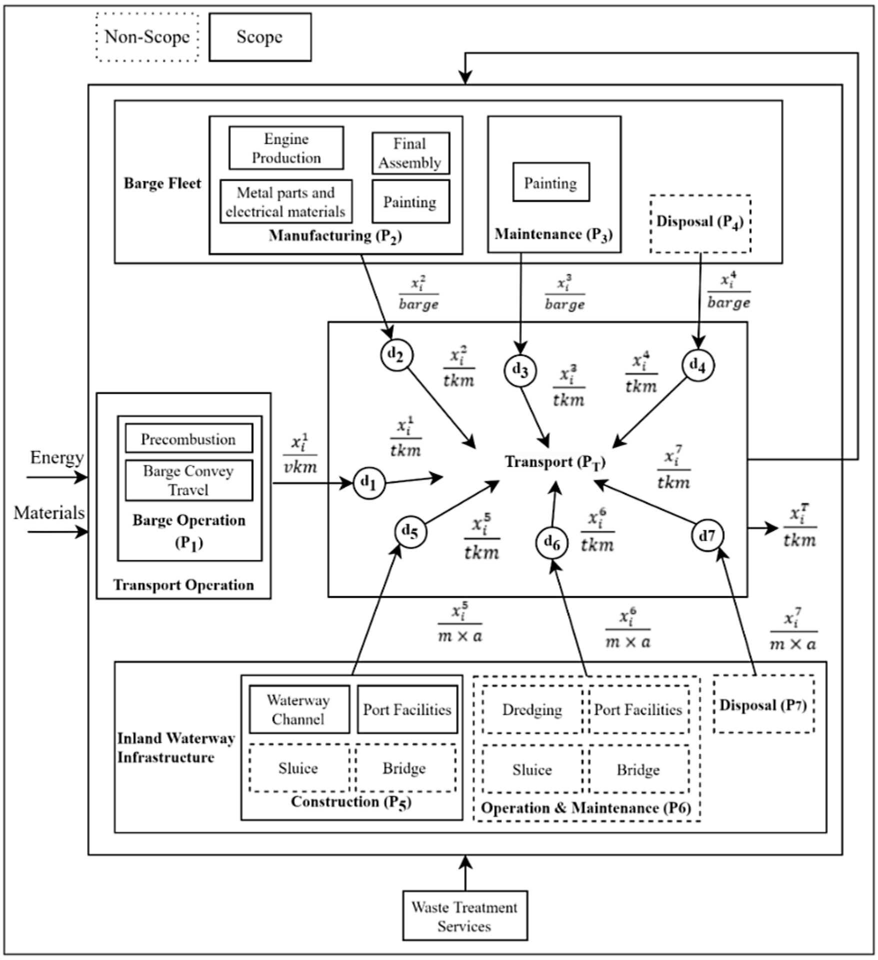

Figure 5. Barge Transport Life Cycle

In this paper, Construction (P_5), Operation and Maintenance (P_6), and Final Disposal (P_4 and P_7) are not considered because they are not involved in the Ecoinvent database.

The components of barge transport services ($p_i, i = 1, \ldots, 7$) are associated with the unit processes (p_T) and referenced in the Ecoinvent database 3.7.1. The demand factors (d_j) presented through the connection between the components a reference flows for a ton-km. The cumulative results in the ICV (x_i^T), measured in ton-km, were calculated using Equation 7 [39]:

$$x_i^T = \sum_{j=1}^{n} \frac{x_i^j}{r(p_j)} \cdot d_j \tag{7}$$

where *n* represents the number of transport service components; and $x_i^j / r(p_j)$ denotes the environmental interactions for a given transport component, considering a unit process (p_j) associated with a reference flow ($r(p_j)$).

4. Results and Discussion

4.1. GWP_{100a} of Barge Convoy

The convoys of 16 and 20 barges had the lowest GWP_{100a} (Figure 6), with an average was 7.55% lower, while the nine barges convoy was 13.03% lower. These values reflect the number of resources and loading capacities of the barge convoys. Although the 20-barge convoy requires additional resources, the high loading capacity does an environmental impact lower in terms of ton-km. In the nine-barge convoy, the loading capacity is limited by 47.50% due to draft restrictions in the dry, making this composition more environmentally damaging.

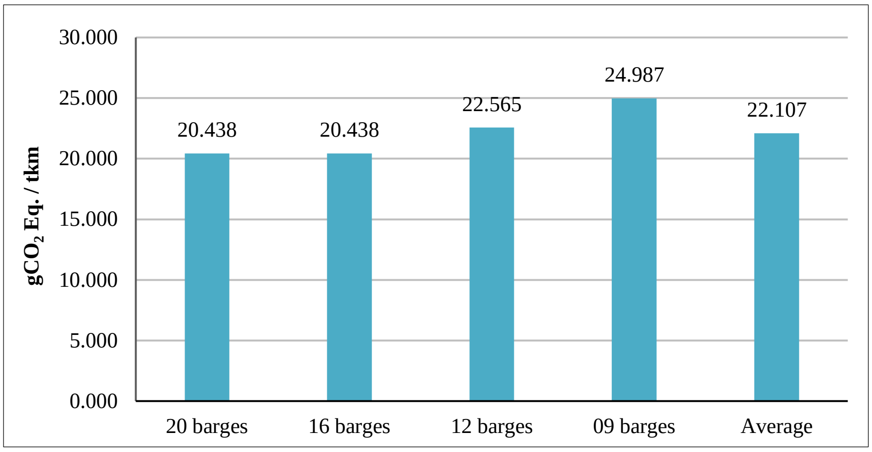

Figure 6. GHG Emission per ton-km of Barge Convoy

As can be seen, the representativeness of GHG emissions in transport operations tends to be higher in lower-capacity trains. In other words, transport operations in drought are more harmful to the environment when compared to the rainy season. GHG emissions from the transport services are presented in Figure 7. An average, the Transport Operation were the most harmful (56.28%), while Barge Fleet and IWT Infrastructure accounted for less than half (43.72%).

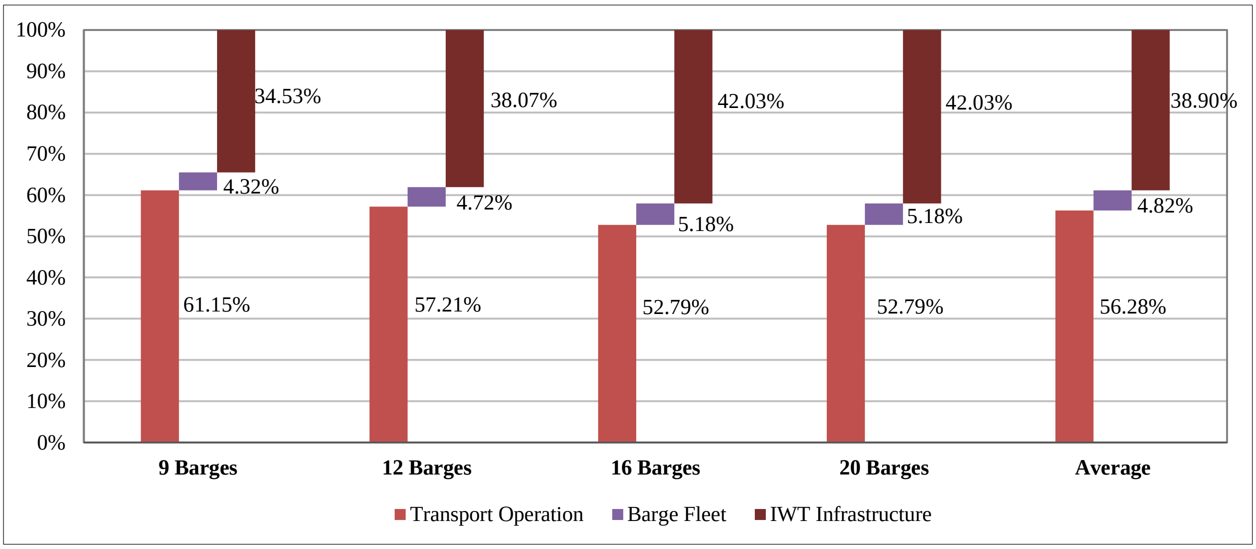

Figure 7. GHG emissions from barge convoy transport service components

In Transport Operations, 89.09% of emissions were generated in barge travel, while the rest (10.91%) in pre-combustion. In the Barge Fleet, barge manufacturing accounted for 76.59% of emissions, while maintenance and final disposal added up to 23.42%. Finally, the construction of the waterway channel accounted for 68.00% of the emissions generated in the infrastructure, while the rest (32.00%) was for the construction of port facilities. The GHG emissions generated from barge trips in this research are within the range of values (maximum and minimum) found in the literature (Figure 8). Fan et al. [19] obtained the closest values (8.70 gCO_2/t.Km). The characteristics of the barge operation are similar; the capacity of the barges is 1880 tons, however the distance travelled is 6,000 km. It seems that the barge operation of Fan et al. [19] is more efficient than the barge operations of this research.

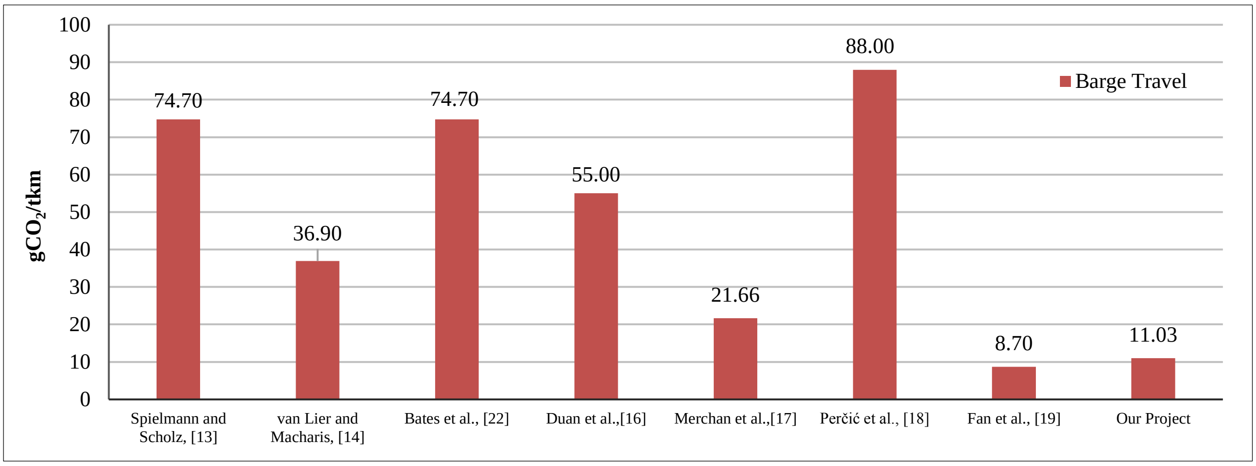

Figure 8. Comparison of GHG emitted in barge trips and the total extracted from the literature

Merchan et al. [17] considered the barges' loading capacity of 1,000 tons over 1417 km, with similar characteristics to this research. Despite this, the barge trips of this research emitted 49.09% less CO_2/t.Km, evidencing an inefficiency of Belgian barge trips, despite the negative impact of drought on Brazilian barge operations. Perčić *et al.* [18] emitted the most GHGs from the barge trips (88.00 CO_2/t.Km). The loading capacity of the barges is 967 tons, 223 km of distance, which may be why barge travel is so harmful to the Chinese environment. Next, the emissions generated due to the hydrological season (rainy and drought season) on the Madeira River are analysed.

4.2. Impact of Drought on Barge Transport

On Madeira River, the low water level occurs in drought season. The navigation restriction's come from the Brazilian Navy. Despite this, 15.35% of the grains took during the drought season, in 2021. Of this total, the convoy of nine barges transported 81.87% of the grains. Figure 9 provides the percentage use of barge convoys and the total $CO_{2Eq.}$ per ton-km emission during 2021. The barge transport increased CO_2 emission according to the lower capacity barge convoys increased the usage fee. In September, barge transportation accumulated the highest $CO_{2Eq.}$ emissions, while the Madeira River had the lowest water level of the year, resulting in 100% of the grains carried by convoys of nine barges. Because of this, $CO_{2Eq.}$ emissions increased by 22.25% compared to the rainy season.

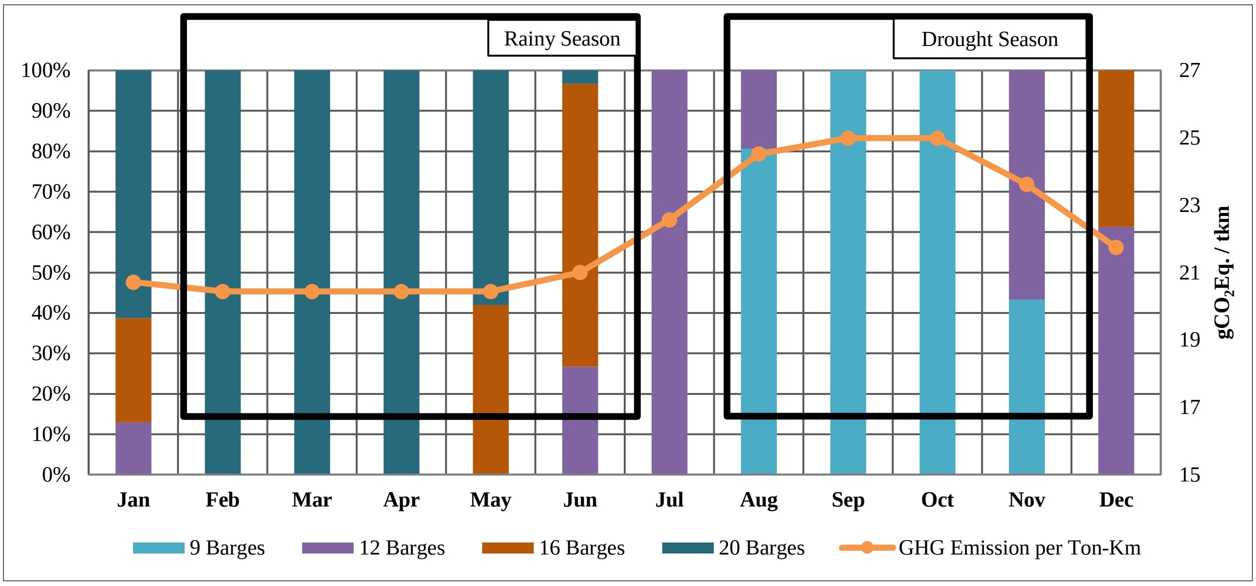

Figure 9. Percentage of use and Total GHG Emissions per ton-km of barge convoys

4.3. Comparison with Land Transport Modes (Rail and Road)

Figure 10 compares the total GHG emission per ton-km among land transport modes (rail, road, and water) and an average amount of GHG emitted per ton-km for each barge convoy. Due to the Ecoinvent databases, the emission data for land transport modes reflects the European context.

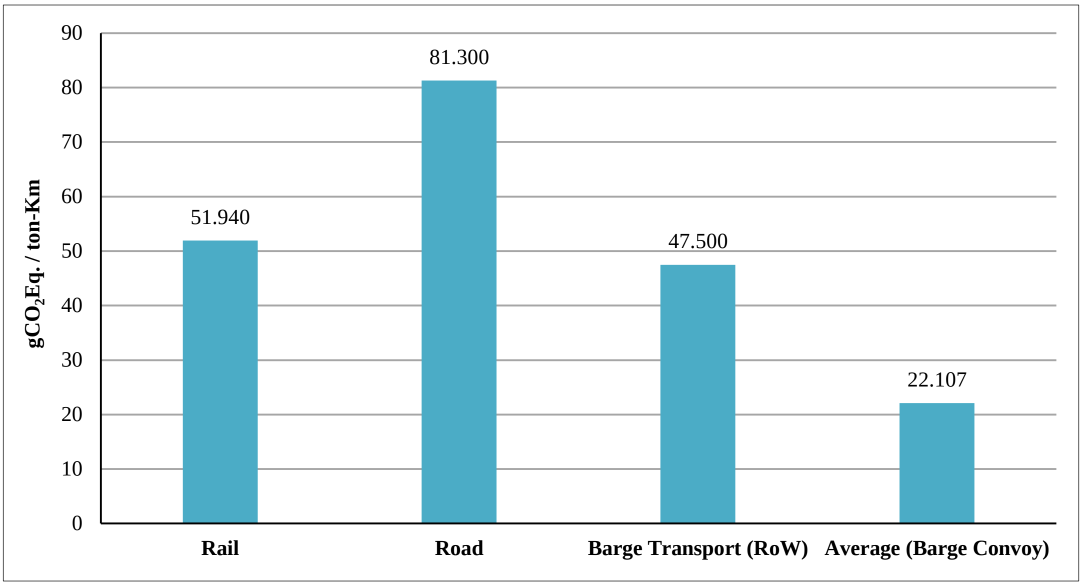

Figure 10. GHG emissions per ton-km of land transport modes

The road, rail, and waterway transport modes emitted 267.67, 134.95, and 114.87% more GHG than barge convey, respectively. In other words, barge transport is the best alternative, despite the increased environmental impact during the drought season.

5. Conclusion

This research aimed to analyze the impact of drought on the life cycle of barge transport in the Madeira River. LCA method was applied to quantify GHG emissions in barge transport, which had three transport services: Transport Operation, Barge Fleet, and Waterway Infrastructure. In the Madeira River, the water level was more than 13 meters amplitude during 2021. In this context, we developed a transport operation model using four barge convoy types according to the water level range. We evaluated the GHG emissions considering the characteristics of the barge convoy (engine power, diesel consumption, and loading capacity). GWP100a was 22.25% higher in the dry season, evidencing that low water levels make barge transport more harmful to the environment. Comparison of GHG emissions from barge transport with land transport modes such as rail, road, and IWT Standard (in the European context). Despite the increase in emissions from barge transport in the drought season, emissions from other land transport modes were at least 114.87% (IWT Standard) higher than the average emission from barge convoys. Road transport was the most harmful to the environment, followed by rail transport. The results obtained in this research are valid only for the barge transport on the Madeira River, which may not be for other case studies. Indeed, different characteristics between rivers must be considered, such as navigation restrictions during low water levels, barge convoy configuration according to the range of water levels, and diverse emission engine technologies. However, the presented methodology is directly applicable to evaluating the impact of drought on the life cycle of barge transport in other geographic regions.

6. Declarations

6.1. Author Contributions

Conceptualization, B.T.G.G. and A.S.M.; methodology, B.T.G.G. and A.S.M., F.A.C.N., and M.A.V.S.; software, B.T.G.G.; validation, B.T.G.G., A.S.M., F.A.C.N., and M.A.V.S.; formal analysis, B.T.G.G., A.S.M., F.A.C.N. and M.A.V.S.; investigation, B.T.G.G., and A.S.M.; resources, B.T.G.G., A.S.M., and M.A.V.S.; data curation, B.T.G.G.; writing—original draft preparation, B.T.G.G. and A.S.M.; writing—review and editing, B.T.G.G., A.S.M., F.A.C.N. and M.A.V.S.; visualization, F.A.C.N. and M.A.V.S; supervision, M.A.V.S; project administration, B.T.G.G.; funding acquisition, B.T.G.G.. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

Data sharing is not applicable to this article.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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